Aerosol Reanalysis at GMAO

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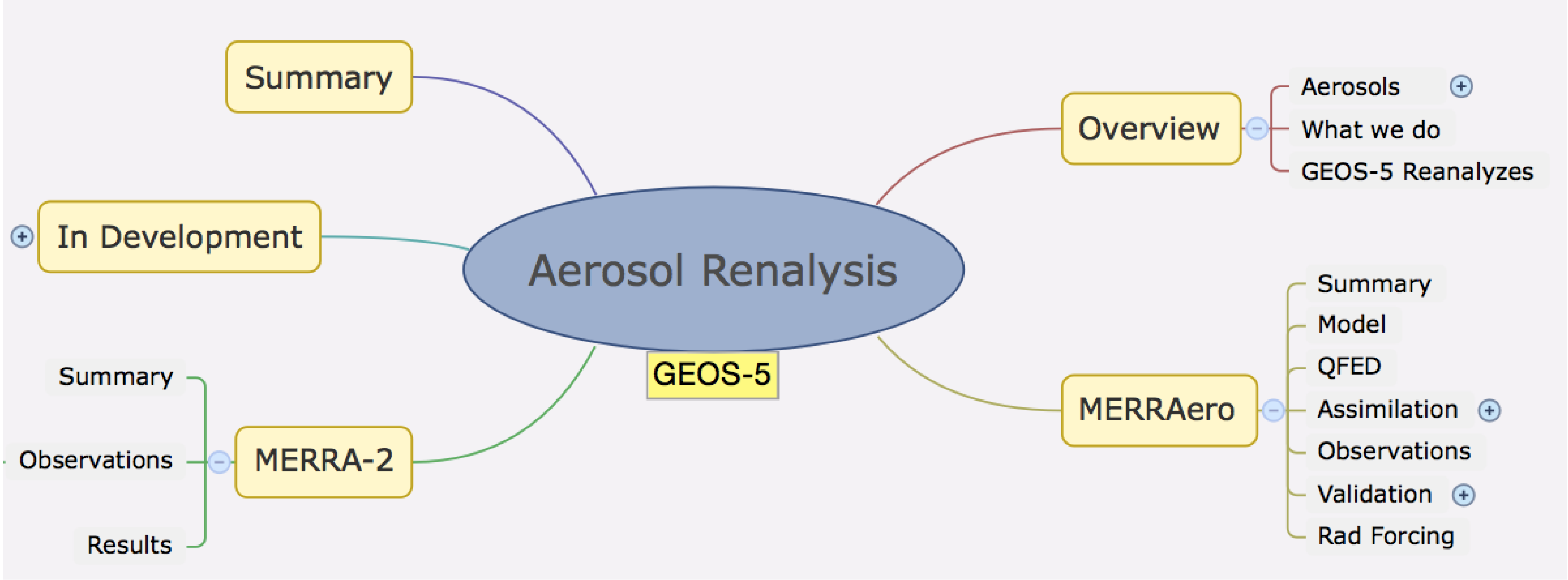
With contributions from Peter Colarco, Anton Darmenov, Virginie Buchard, Gala Wind, Cynthia Randles, Ravi Govindaradju and many others

NOAA Climate Reanalysis Task Force Workshop
College Park, Maryland
4-5 May 2015

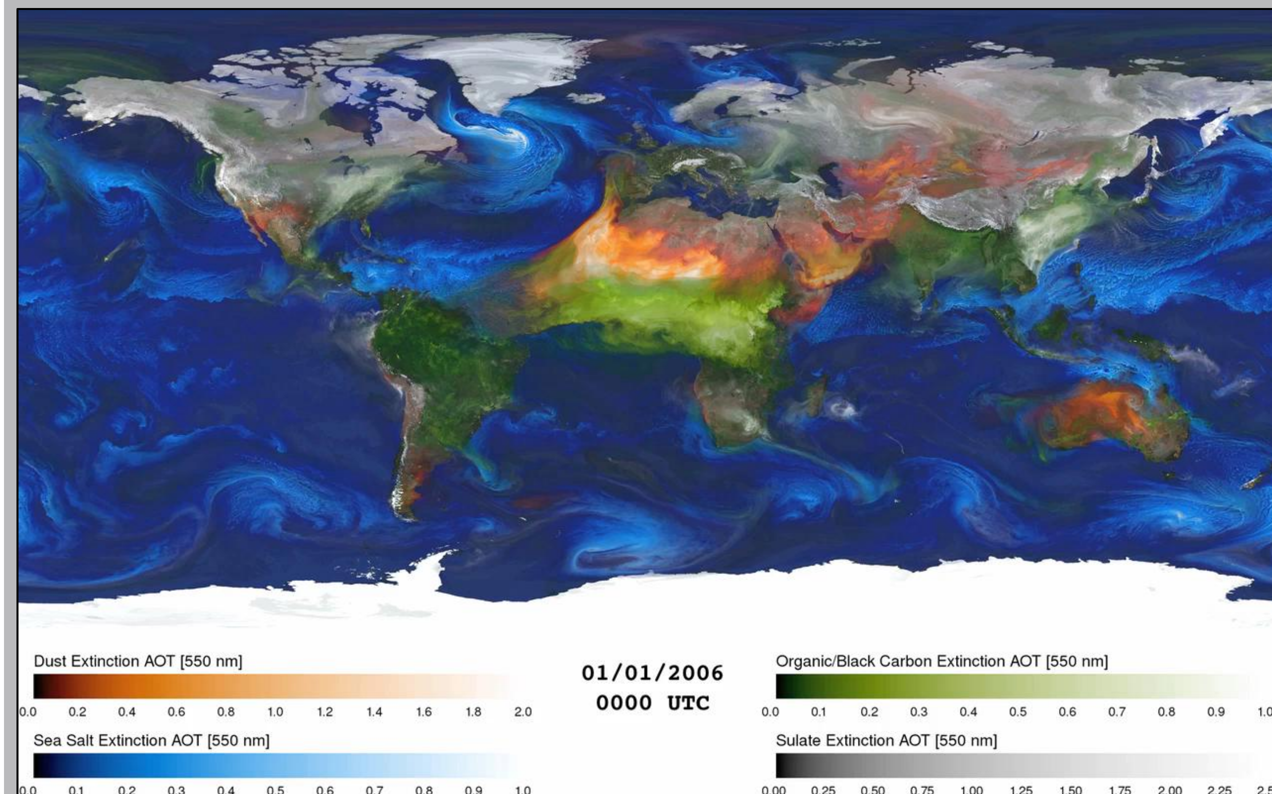
Outline


Aerosol Renalysis
GEOS-5
Summary
In Development
MERRA-2
Summary
Observations
Results
Overview
Aerosols
What we do
GEOS-5 Reanalyzes
MERRAero
Summary
Model
QFED
Assimilation
Observations
Validation
Rad Forcing

Global Aerosols

7 km GEOS-5 Nature Run
Global Mesoscale Simulation

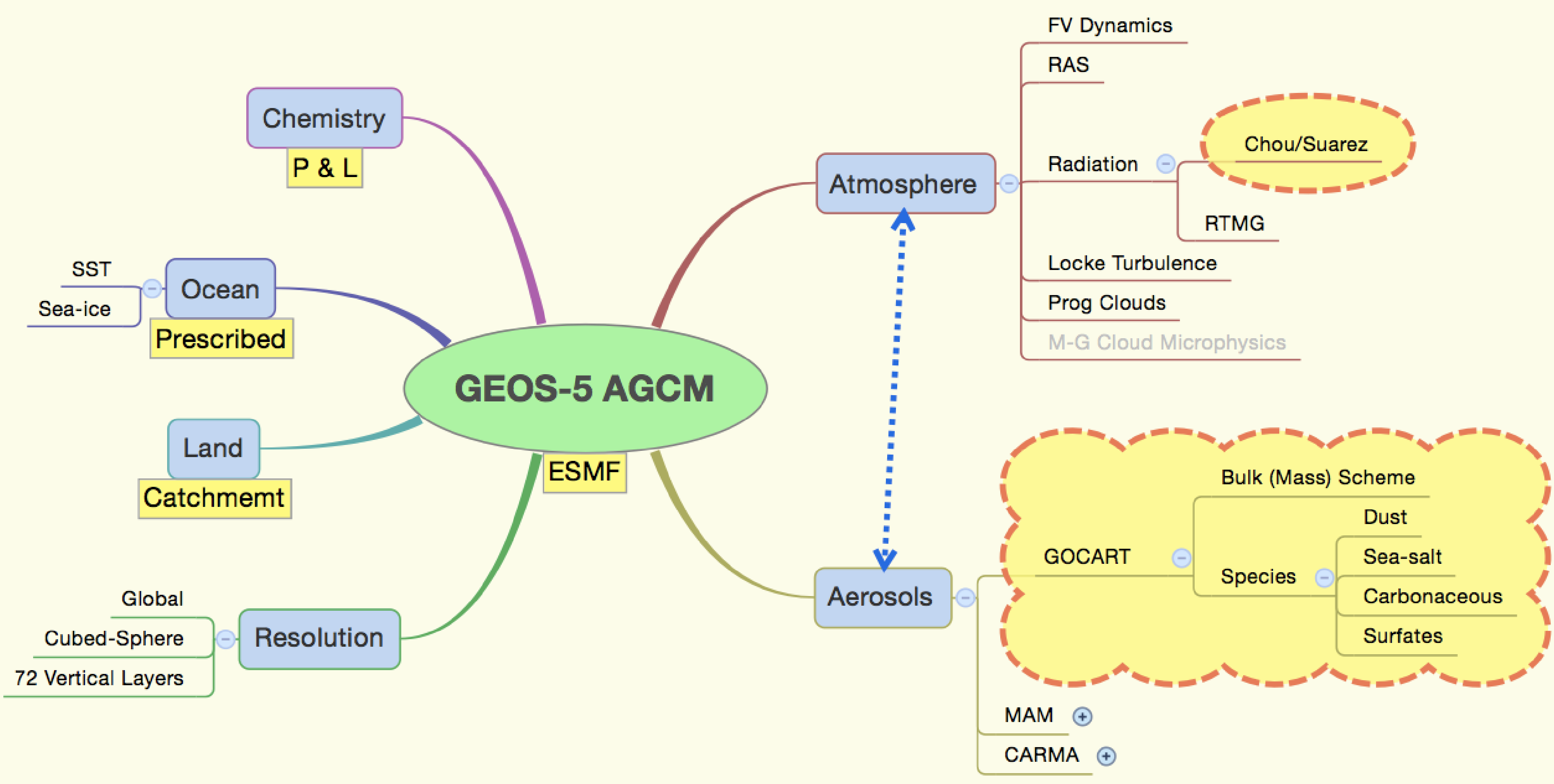
Aerosols play an important role in both weather and climate. They are transported around the globe far from their source regions, interacting with weather systems, scattering and absorbing solar and terrestrial radiation, and modifying cloud micro- and macro-physical properties. They are recognized as one of the most important forcing agents in the climate system.



Summary of GEOS-5 Reanalysis Activities

Name	Nominal Resolution	Period	Aerosol Data	Available
MERRA-1	50 km	1979-present	NONE	now
MERRAero	50 km	2002-present	MODIS C5	now
FP for Inst. Teams	50 km	1997-	MODIS C5	In progress
NCA	25 km	2010-11	MODIS C5, MISR	Now
MERRA-2	50 km	1979-present	AVHRR, MODIS C5, MISR,AERONET	Summer 2015
MERRA-2 Dynamical Downscaling	12.5 km	2000-2015	AVHRR, MODIS C5/C6, MISR, AERONET	Q4 2015

GEOS-5 Model Configuration for and MERR*Aero* MERRA-2

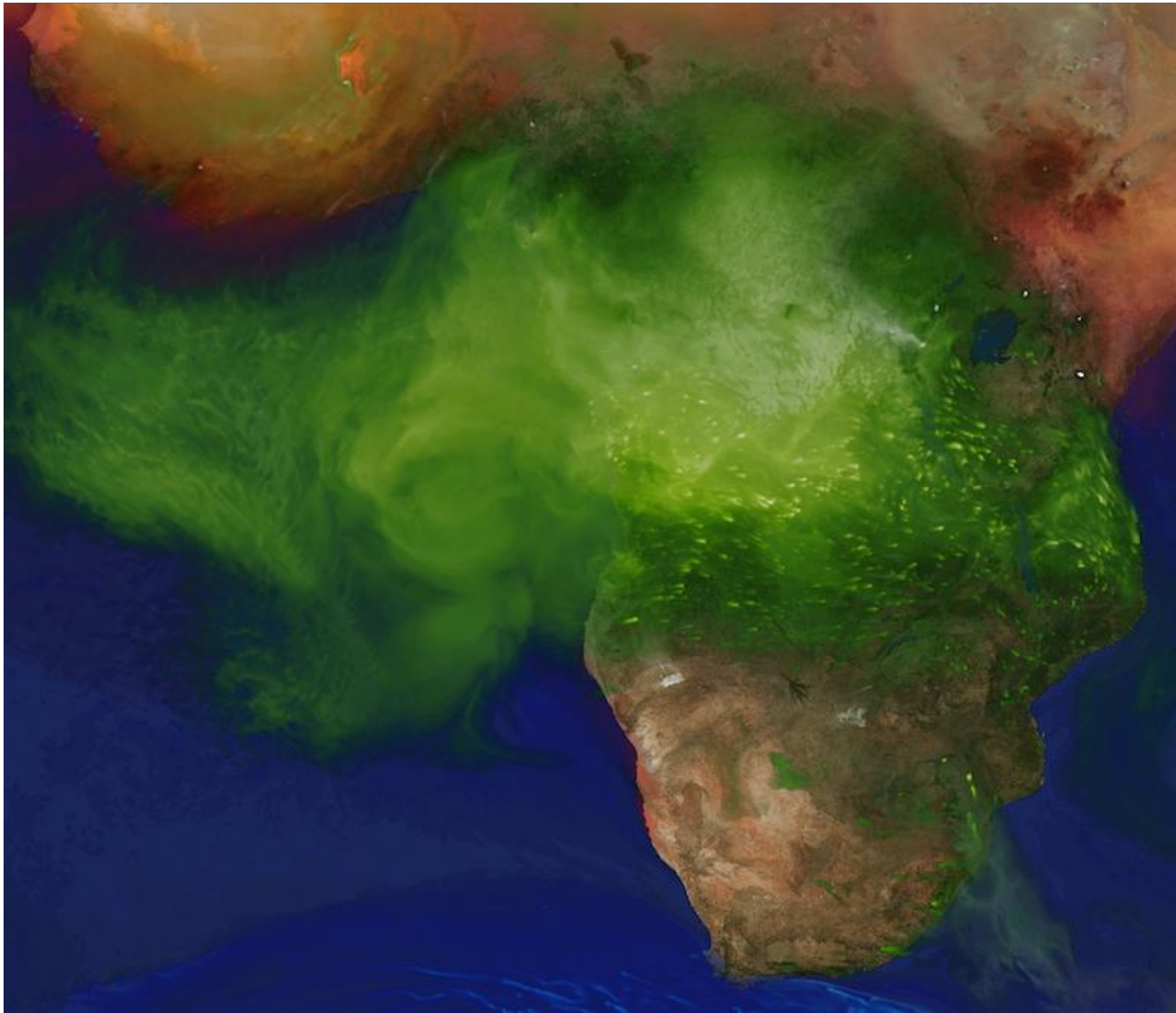


Global, 50 km, 72 Levels, top at 0.01 hPa

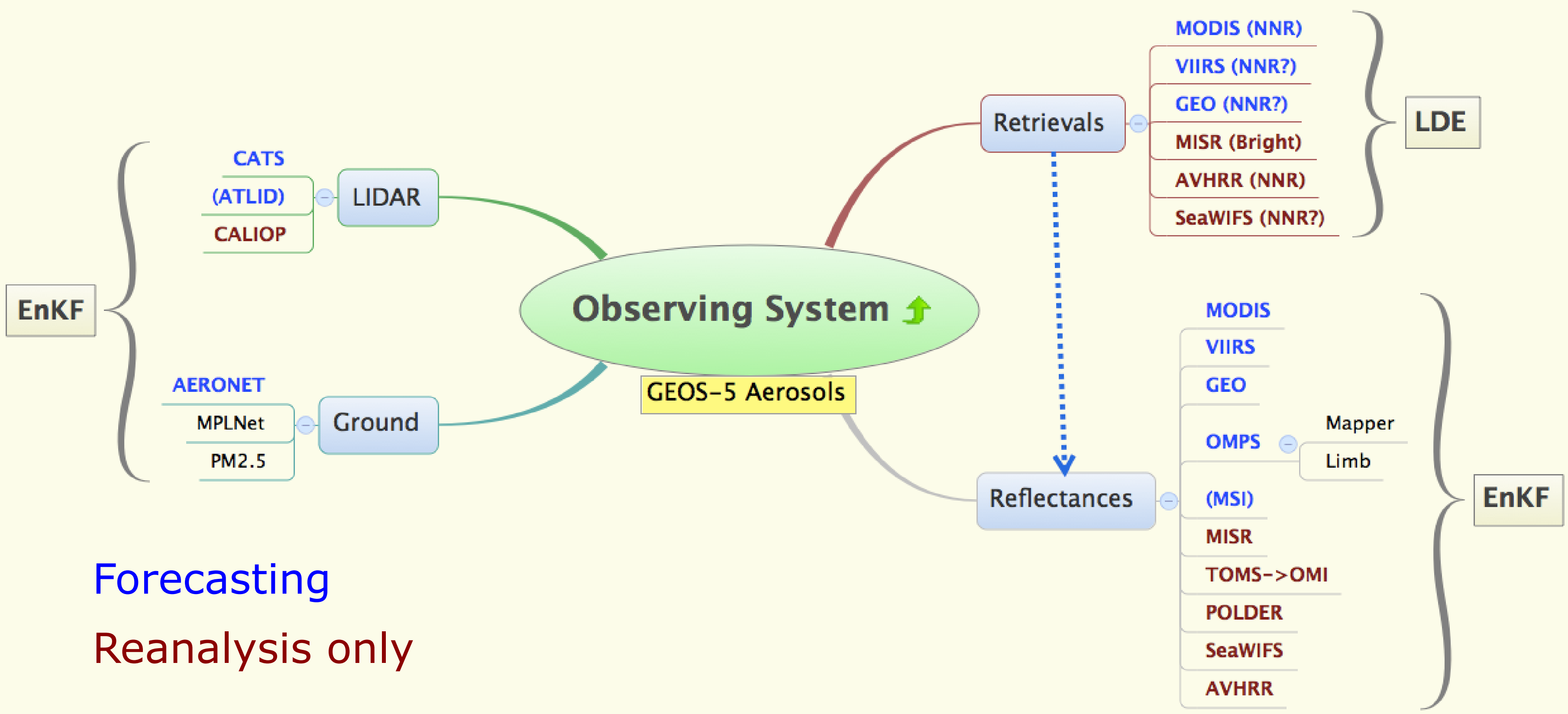
Biomass Burning

QFED: Quick Fire Emission Dataset

- Top-down algorithm based on MODIS Fire Radiative Power (AQUA/TERRA)
- FRP Emission factors tuned by means of inverse calculation based on MODIS AOD data.
- Daily mean emissions, NRT
- Prescribed diurnal cycle
- In GEOS-5 BB emissios are deposited in the PBL.



Aerosol Observing System

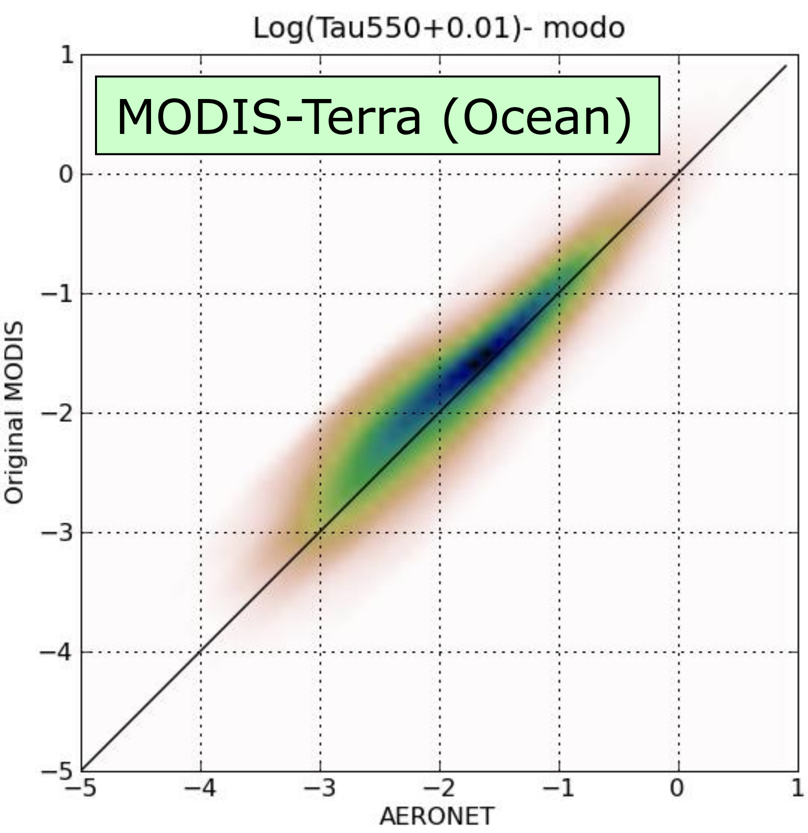


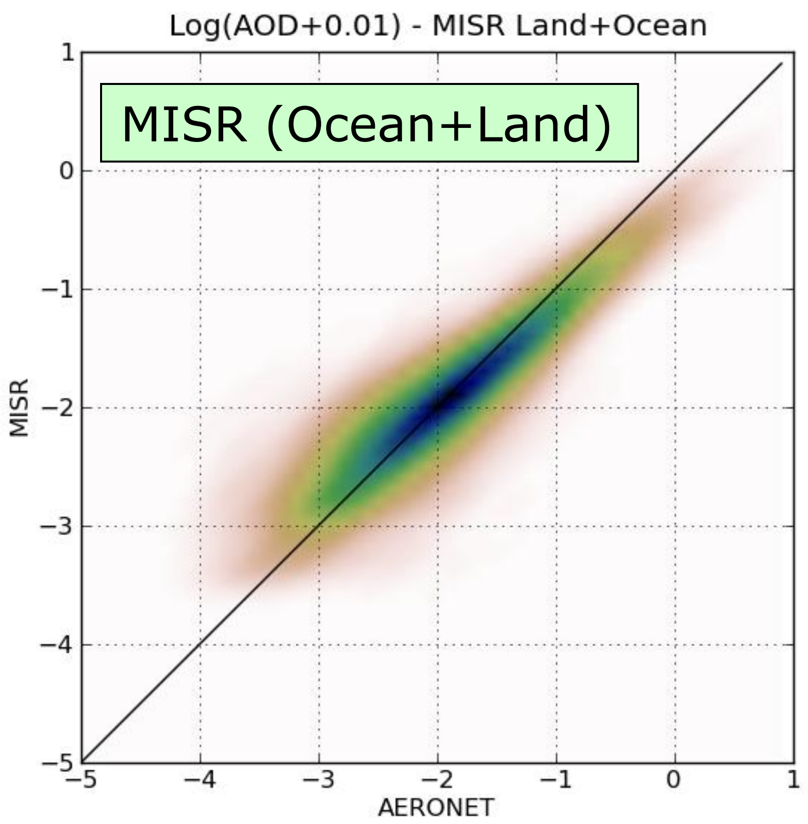
Aerosol Data Assimilation in GEOS-5

MERR*Aero* Overview

Feature	Description
Model	GEOS-5 Earth Modeling System (w/ GOCART) Constrained by MERRA-1 Meteorology (Replay) Land sees obs. precipitation (like MERRA*Land*) Driven by QFED daily Biomass Emissions Version 2.2
Aerosol Data Assimilation	Local Displacement Ensembles (LDE) Neural Net MODIS Aerosol Optical Depth Retrievals • Trained on AERONET Level 2 AOD's Stringent cloud screening
Period	mid 2002-present (Aqua + Terra)
Resolution	Horizontal: nominally 50 km Vertical: 72 layers, top ~85 km
Aerosol Species	Dust, sea-salt, sulfates, organic & black carbon

AERONET-MODIS/MISR Joint PDF





Observation bias correction is necessary.

NRL Empirical AOD Corrections

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D22207, doi:10.1029/2005JD006898, 2006

Click Here for Full Article

MODIS aerosol product analysis for data assimilation: Assessment of over-ocean level 2 aerosol optical thickness retrievals

Jianglong Zhang[1,2] and Jeffrey S. Reid[1]

Received 16 November 2005; revised 1 March 2006; accepted 10 July 20

[1] Currently, the Moderate-resolution Imaging Spect
aerosol product (MOD04/MYD04) is the best aerosol
near-real-time aerosol data assimilation. However, a c
variances in MOD04/MYD04 aerosol optical depth p
implementing the MODIS aerosol product in aerosol
1 year's worth of Sun photometer and MOD04/MYD
over global oceans, we studied the major biases in MO
to wind speed, cloud contamination, and aerosol micr
than 0.6, we found similar uncertainties in the mean M
the MODIS aerosol group, while biases are nonlinear f

An over-land aerosol optical depth data set for data assimilation by filtering, correction, and aggregation of MODIS Collection 5 optical depth retrievals

E. J. Hyer[1], J. S. Reid[2], and J. Zhang[3]

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Received: 12 August 2010 – Accepted: 14 August 2010 – Published: 14 September 2010

Correspondence to: E. J. Hyer (edward.hyer@nrlmry.navy.mil)

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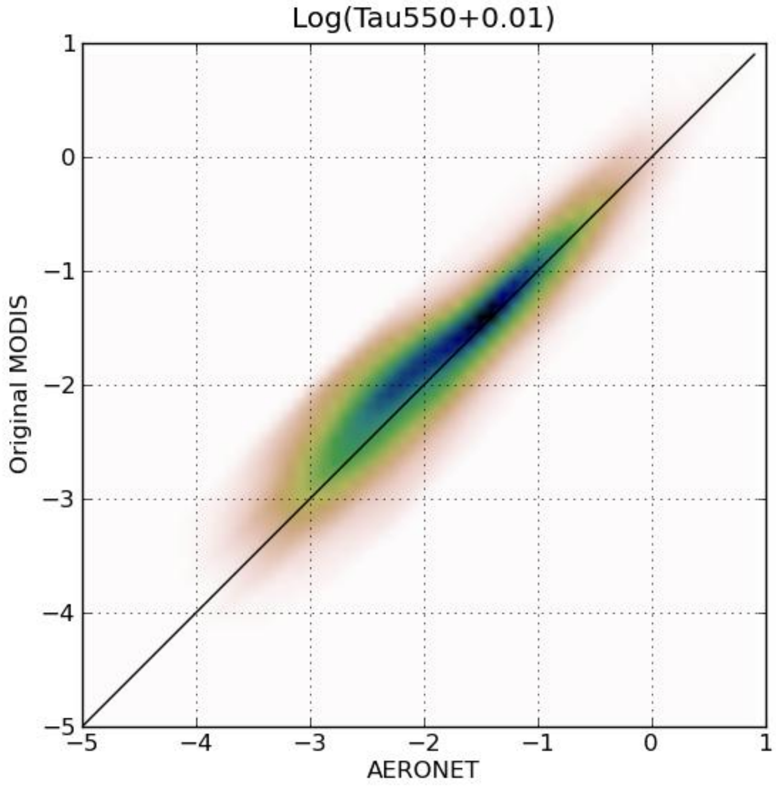
Neural Net for AOD Empirical Retrievals

- Ocean Predictors
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Glint
    - Solar
    - Sensor
  - Cloud fraction (<85%)
  - Wind speed
- Target: AERONET
  - Log(AOD+0.01)

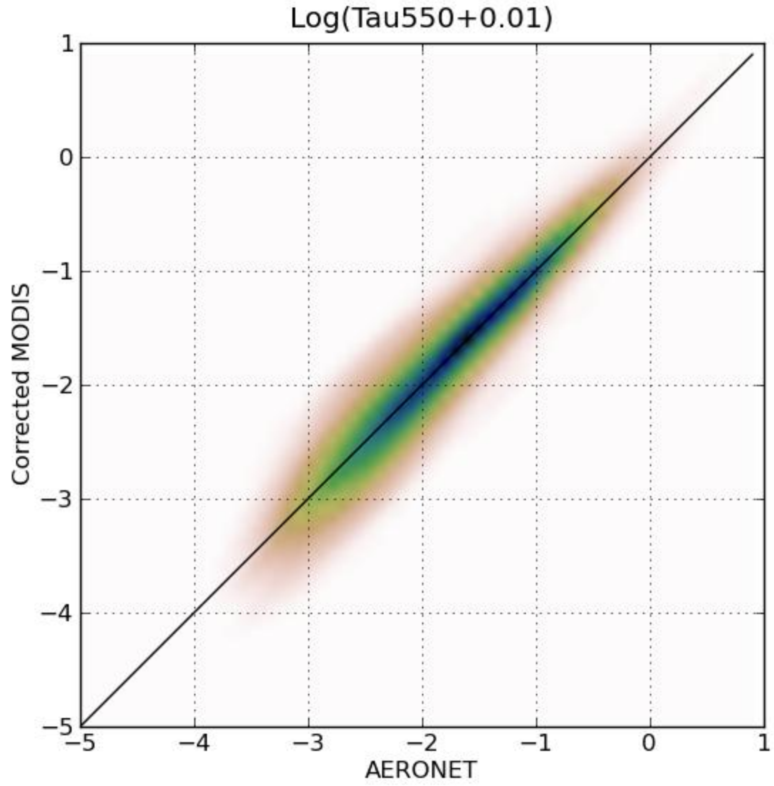
- Land Predictors
  - Multi-channel
    - TOA Reflectances
    - ~~Retrieved AOD~~
  - Angles
    - Solar
    - Sensor
  - Cloud fraction (<85%)
  - Climatological albedo
    - < 0.25
- Target: AERONET
  - Log(AOD+0.01)

Observational Bias

ORIGINAL MODIS AOD



BIAS CORRECTED AOD



Analysis Splitting

3D Aerosol Concentration Analysis

$$x^a = x^f + P^f H^T \left(HP^f H^T + R\right)^{-1} \left(y^o - Hx^f\right) \equiv x^f + \delta x^a$$

where y is AOD, and x is aerosol concentration.

2D AOD Analysis

Since the AOD observable is 2D is common to solve the AOD analysis equation:

$$y^a \equiv Hx^a = y^f + HP^f H^T \left(HP^f H^T + R\right)^{-1} \left(y^o - Hx^f\right) \equiv y^f + \delta y^a$$

Projecting AOD into Concentration Increments

The 3D concetration increments is related to the 2D AOD increments by:

$$\delta x^a = P^f H^T \left(HP^f H^T\right)^{-1} \delta y^a$$

For efficiency, this last equation can be solved in 1D (vertical).

Analysis Splitting with Ensembles

If the background error covariance P^f is parameterized in terms of ensemble perturbations, say

$$\begin{aligned} X &= \begin{pmatrix} x_1 & x_2 & \cdots & x_E \end{pmatrix} \\ Y &= HX \\ &= \begin{pmatrix} Hx_1 & Hx_2 & \cdots & Hx_E \end{pmatrix} \\ &= \begin{pmatrix} y_1 & y_2 & \cdots & y_E \end{pmatrix} \end{aligned}$$

so that

$$P^f \sim XX^T$$

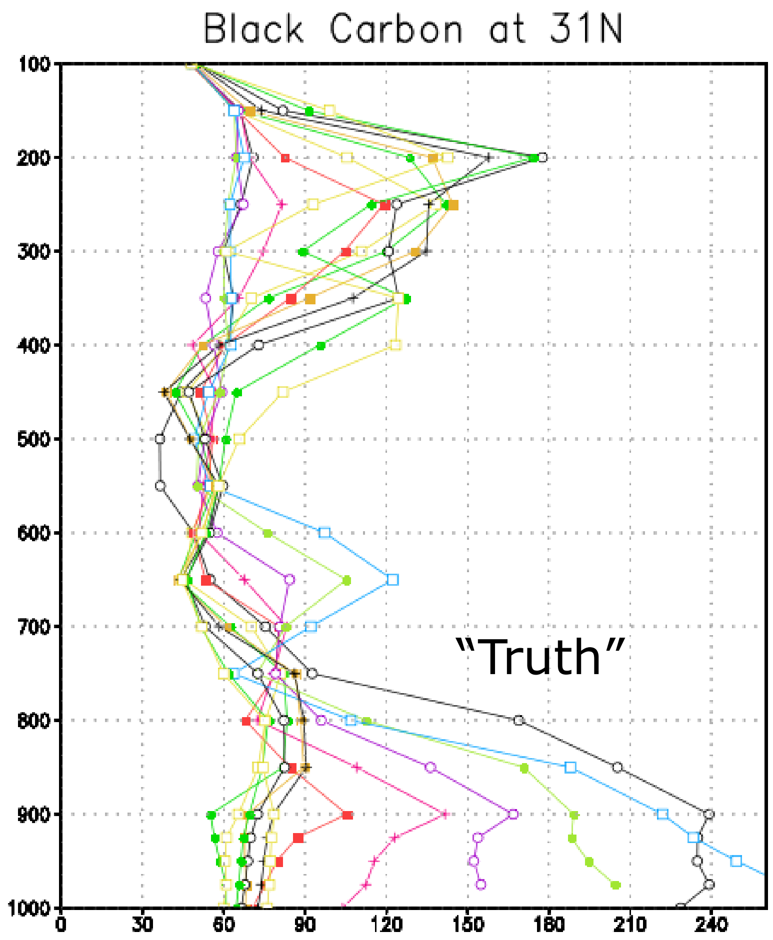
it follows that

$$\delta x^a = XY^T \left(YY^T\right)^{-1} \delta y^a$$

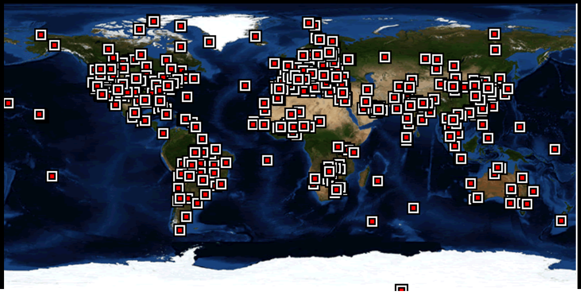
This is the well known (unbiased) linear regression equation.

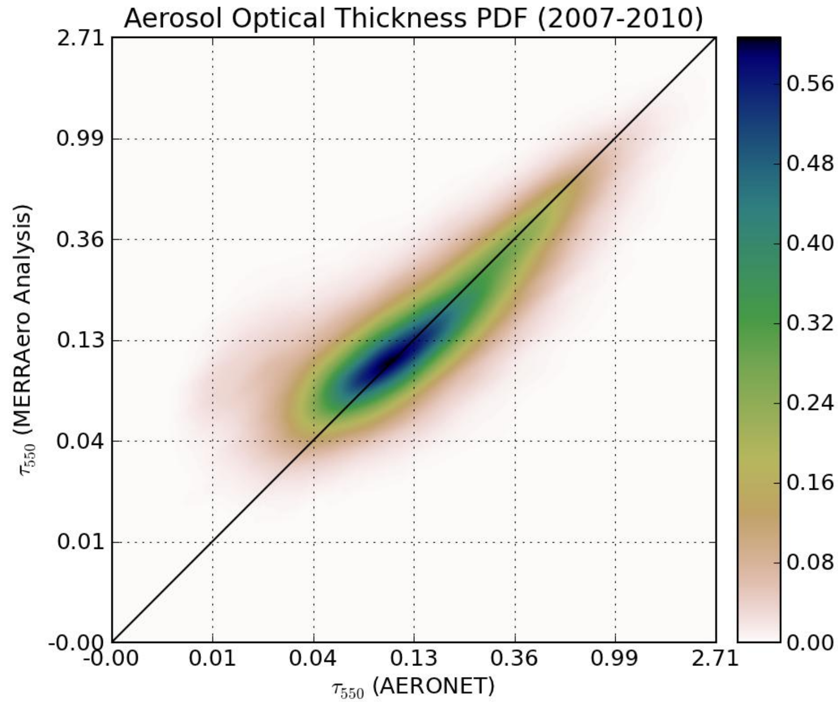
Lagrangian Displacement Ensembles (LDE)

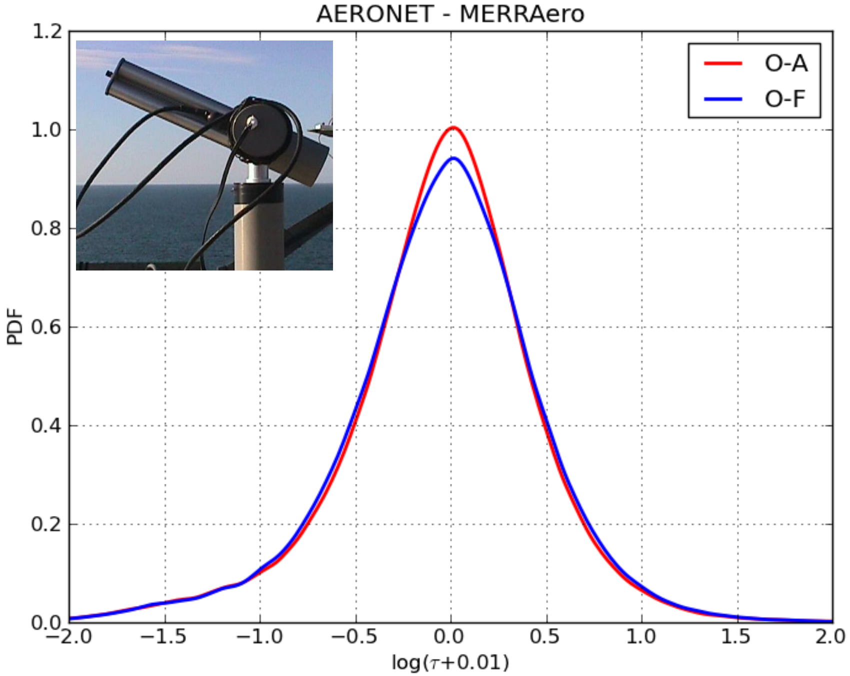
- Construct perturbation ensembles by means of isotropic displacements around gridbox
- Weigh each ensemble member by its fit to 2D AOD analysis
- For efficiency, perform the AOD-to-mixing ratio calculation in 1D



AERONET MERRAero Validation

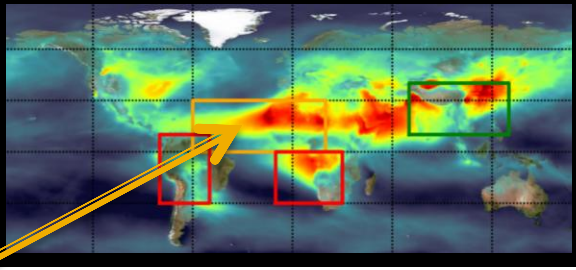




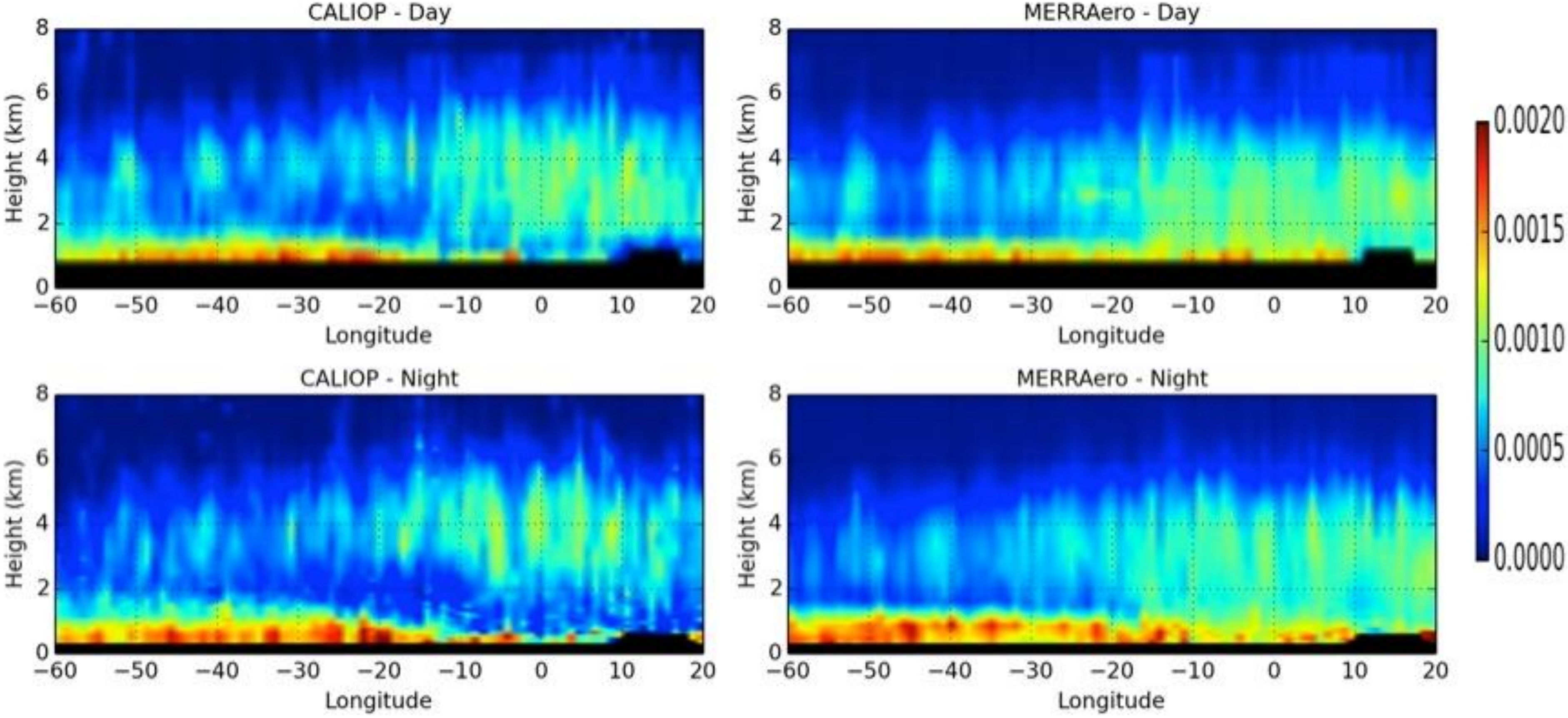


$$\boxed{h = \log(t + 0.01)}$$

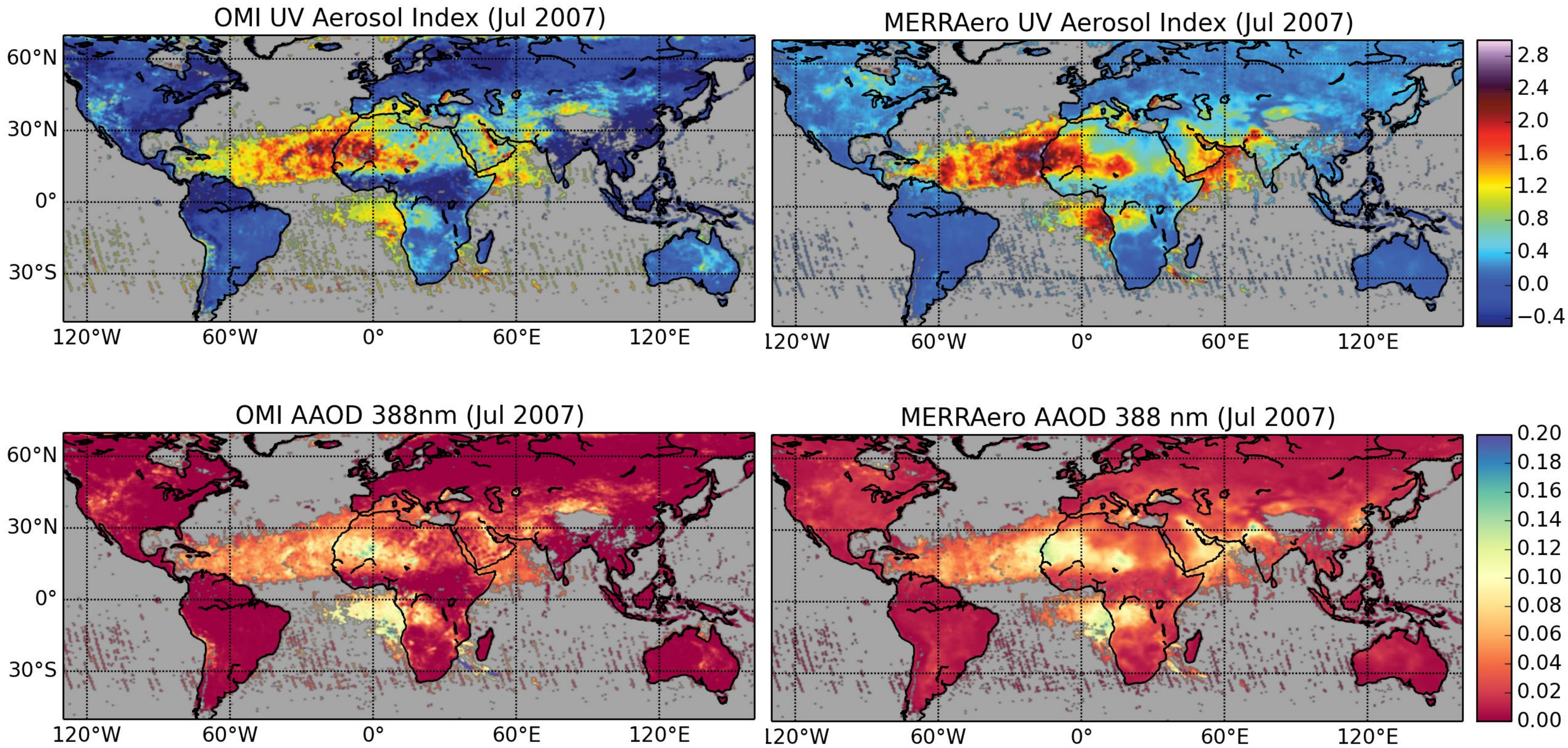
Vertical Structure: Comparison to CALIOP



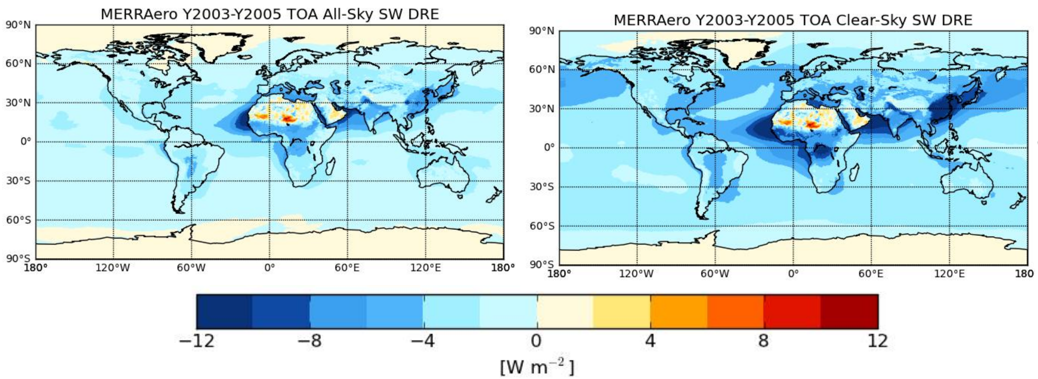
DUST

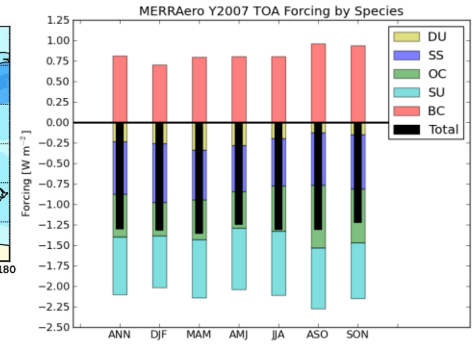


Evaluation of MERRAero Absorption using OMI



MERRAero Aerosol Reanalysis

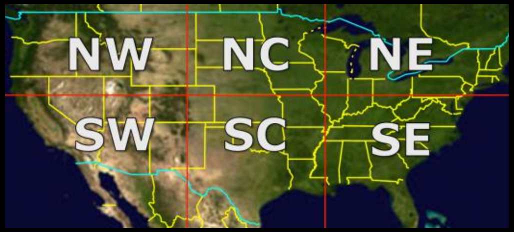


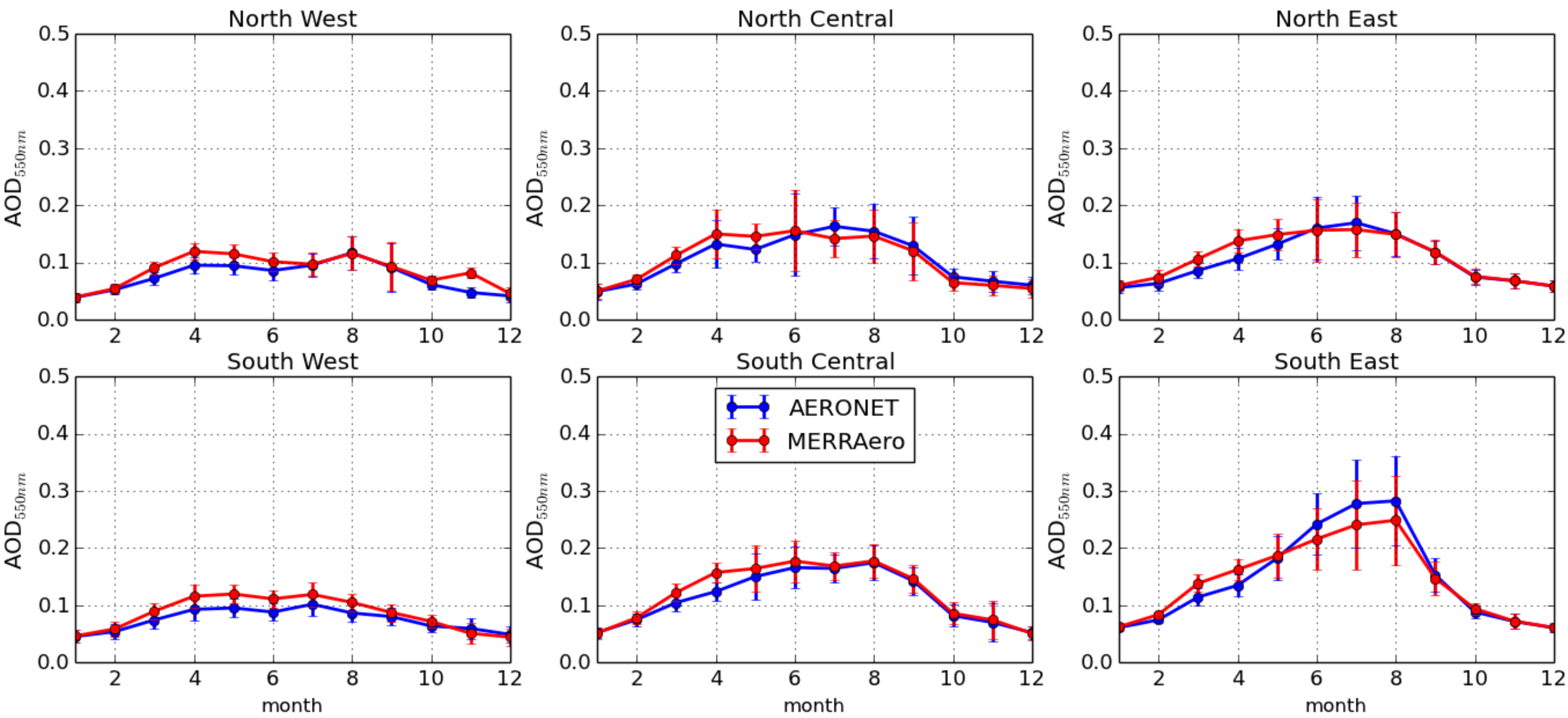


Comparison of globally averaged SW clear-sky aerosol direct radiative effect (DRE)			
Source	TOA SW DRE Ocean (Land)	ATM SW DRE Ocean (Land)	SFC SW DRE Ocean (Land)
MERRAero (Y2003-Y2005)	-3.5 (-3.2)	2.2 (5.4)	-5.7 (-8.6)
Observational (Y2000-Y2003) Yu *et al.* (2006)	-5.5 ± 0.7 (-4.9 ± 0.5)	3.3 (6.8)	-8.8 ± 1.7 (-11.7 ± 1.2)
Multi-Model (Y2000-Y2003) Yu *et al.* (2006)	-3.5 ± 1.3 (-2.8 ± 1.2)	1.3 (4.4)	-4.8 ± 1.6 (-7.2 ± 1.9)

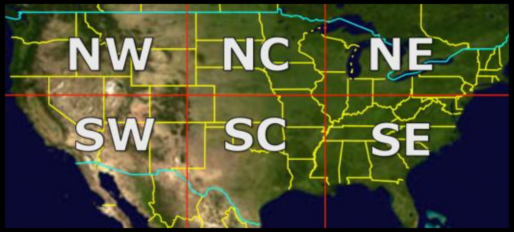
MERRAero provides observation constrained estimate of aerosol radiative forcing, which can be analyzed by component

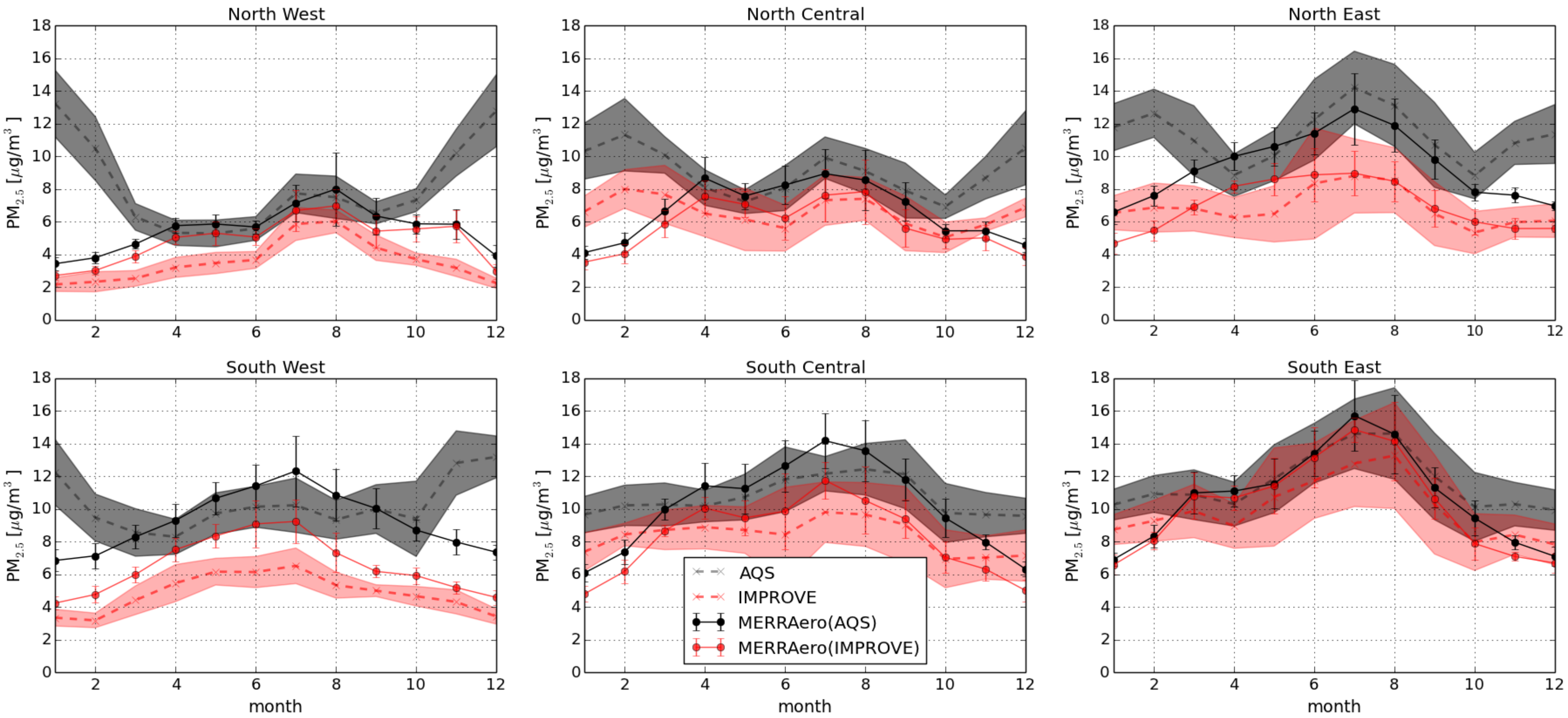
Aerosol Optical Depth Regional Climatology





$PM_{2.5}$ (Total) Regional Climatology



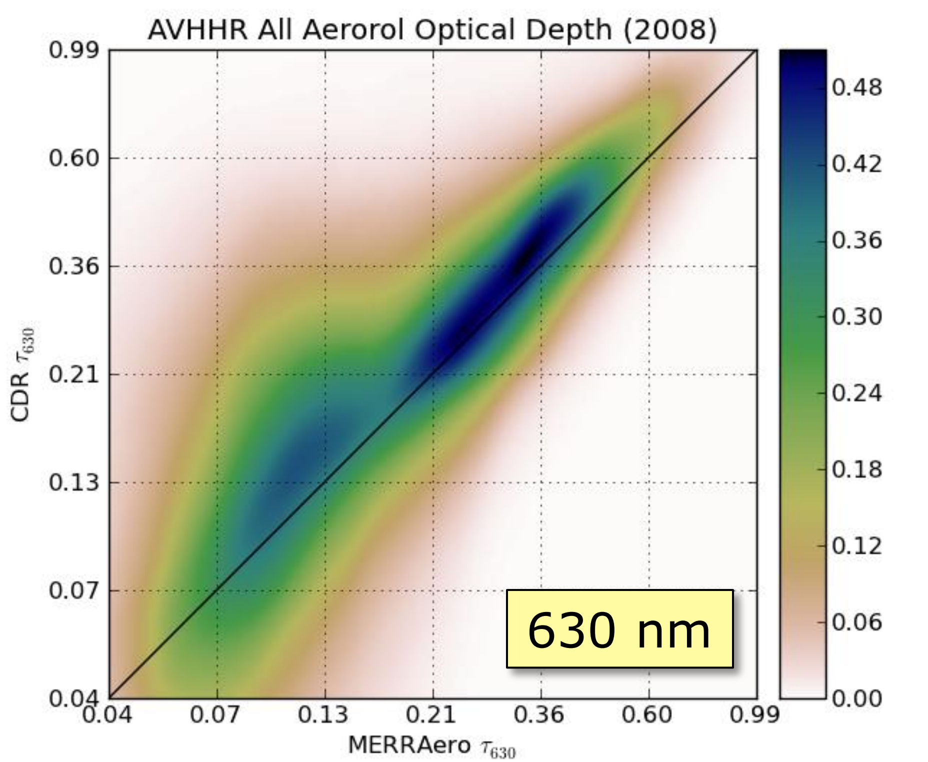


Aerosols in MERRA-2

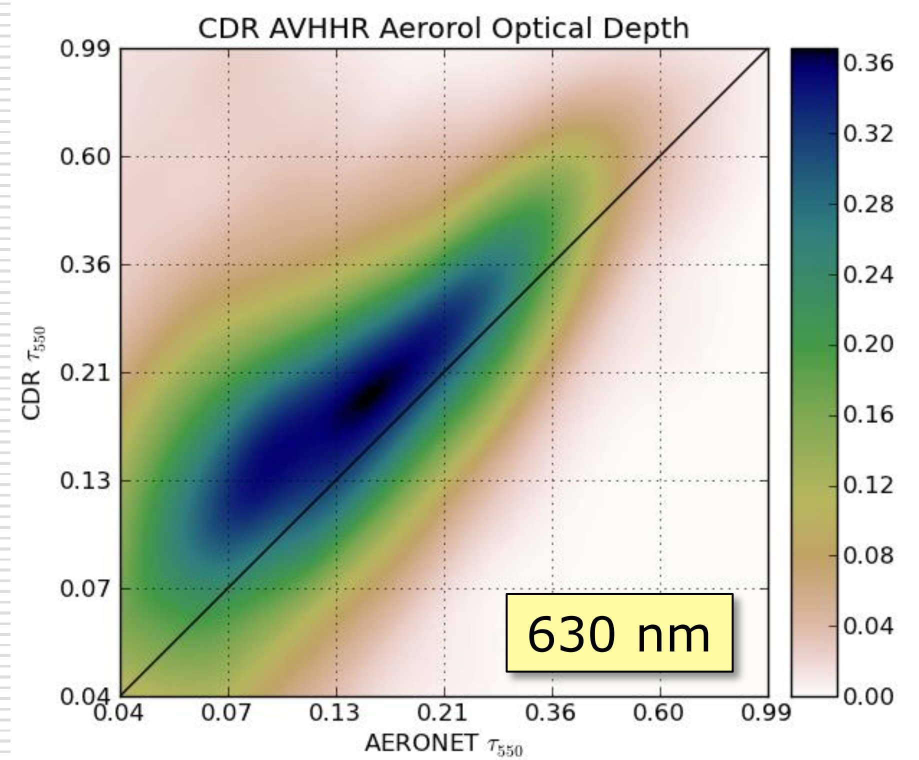
Feature	Description
Model **Emissions**	GEOS-5 Earth Modeling System (w/ GOCART) Interactive aerosols with AOD data assimilation Land sees obs. precipitation (like MERRA*Land*) Daily QFED for 2000-on, monthly calibrated RETRO before
Aerosol Data Assimilation	Local Displacement Ensembles (LDE) Neural Net MODIS Aerosol Optical Depth Retrievals v2 MISR AOD data over bright surfaces AVHRR Neural Net Retrieval Stringent cloud screening
Period	1980-present
Resolution	Horizontal: nominally 50 km Vertical: 72 layers, top ~85 km
Aerosol Species	Dust, sea-salt, sulfates, organic & black carbon

AVHRR NOAA CDR AOD

MERRAero, AERONET Comparison

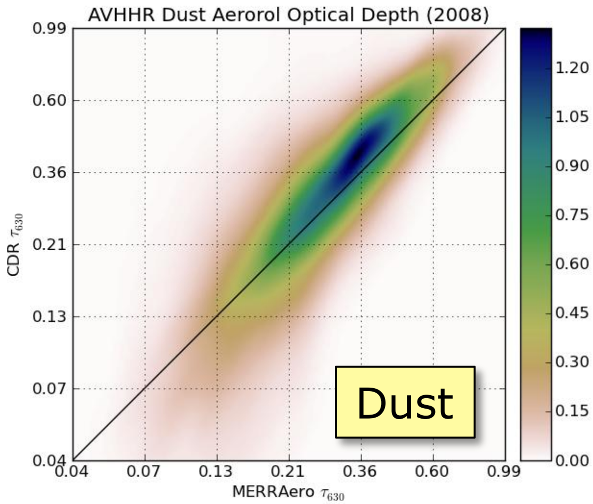


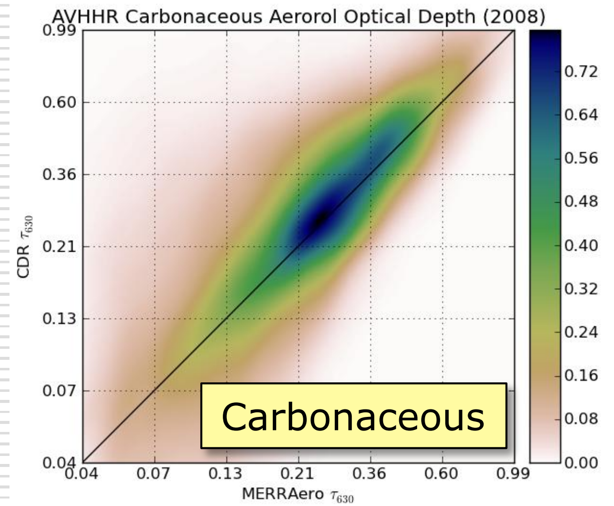
MERRAero

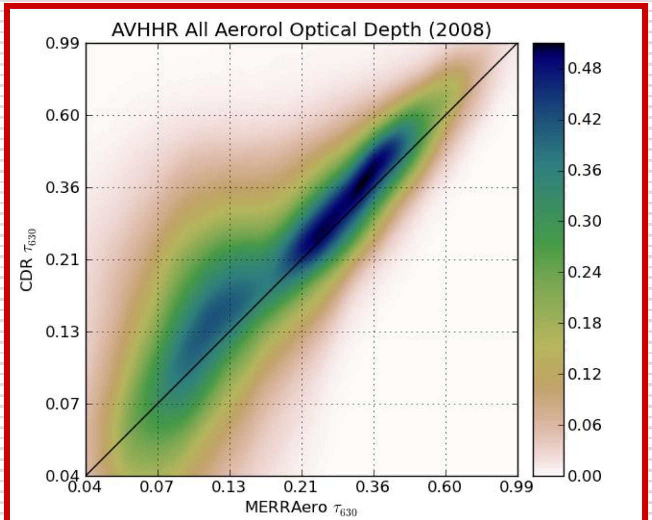


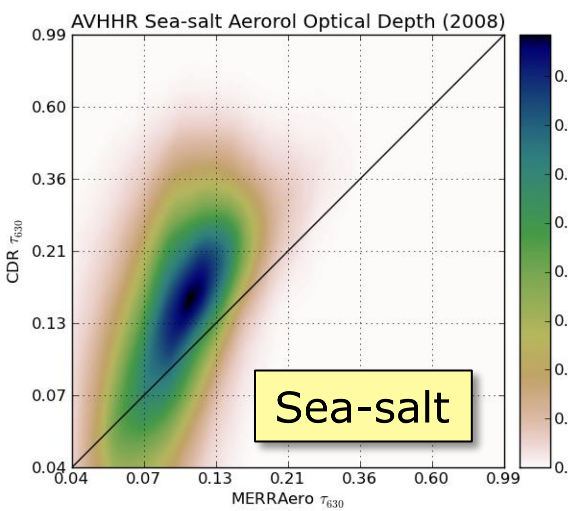
AERONET

CDR: 2008

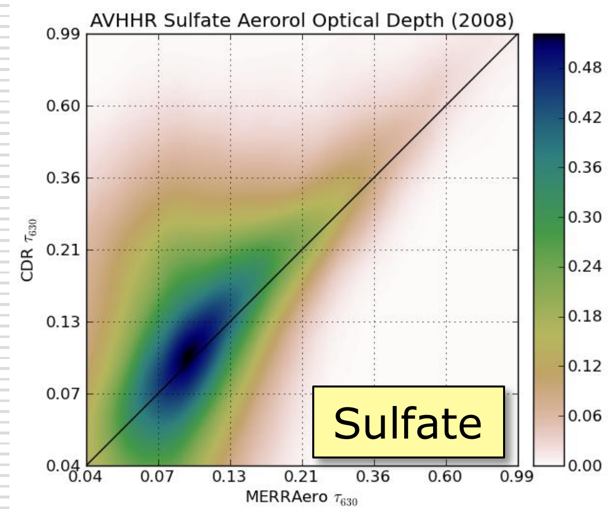








Multiple Species



PATMOS-x

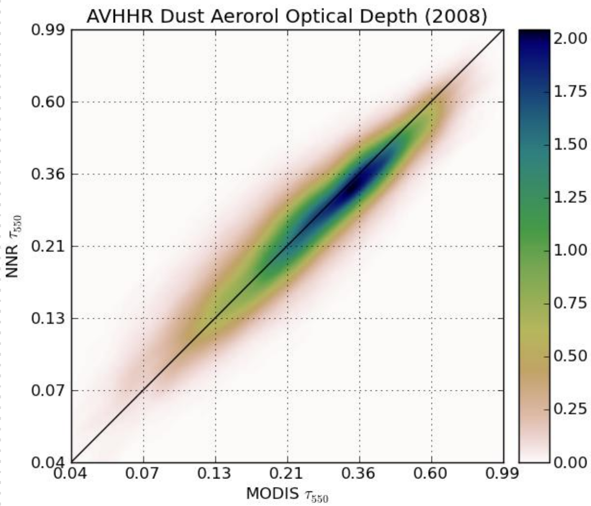
AVHRR Pathfinder Atmospheres - Extended

PATMOS-x Dataset

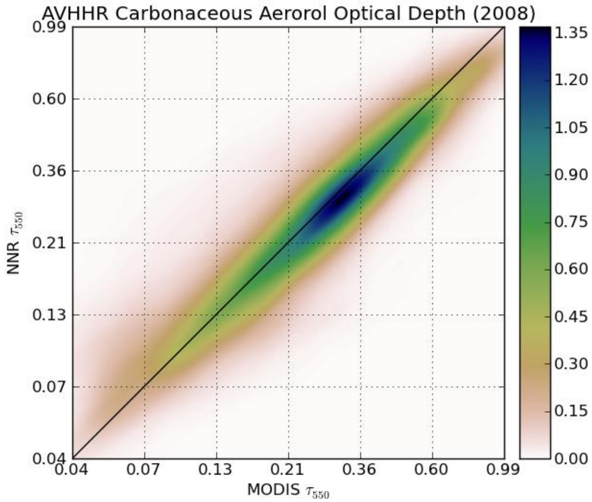
- Version 5 Level 2B
- 0.1 degree sampling (not average)
- Period: 1978-2009
- Inter satellite calibration (MODIS reference)
- Bayesian probabilistic cloud detection (CALIPSO reference)
  - **cpd <0.5%**

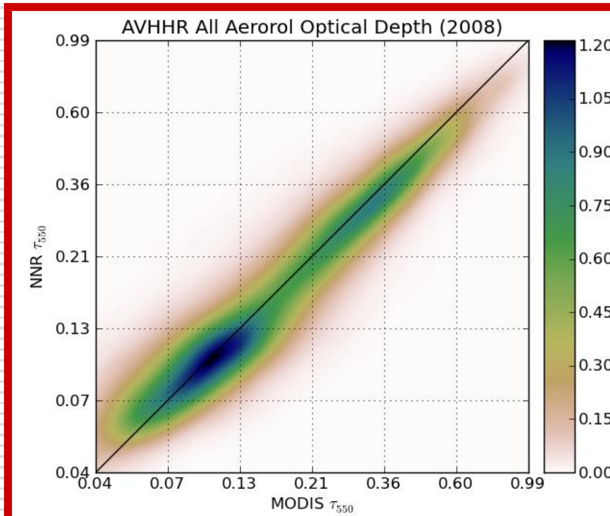
Neural Net Retrival

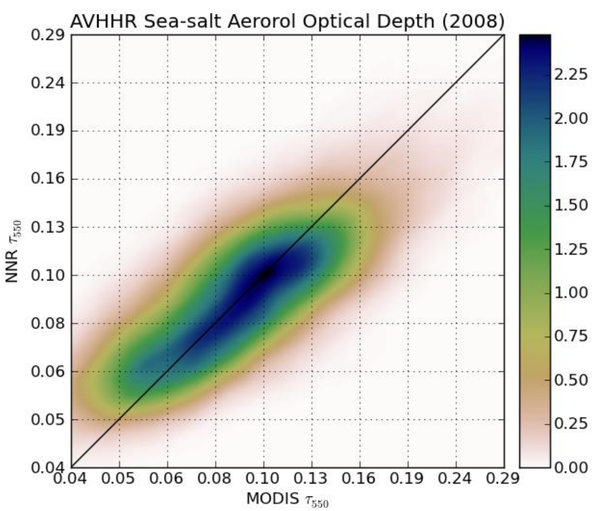
- Ocean Predictors
  - TOA Reflectances
  - 630 and 860 nm
  - TPW
  - Ocean albedo (wind)
  - Solar and sensor angles
  - GEOS-5 fractional AOD speciation
- Target:
  - AOD at 550 nm
  - Balanced MODIS NNR



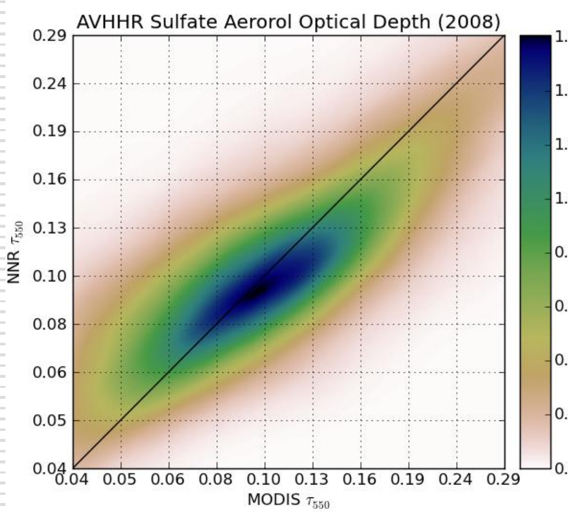
2008

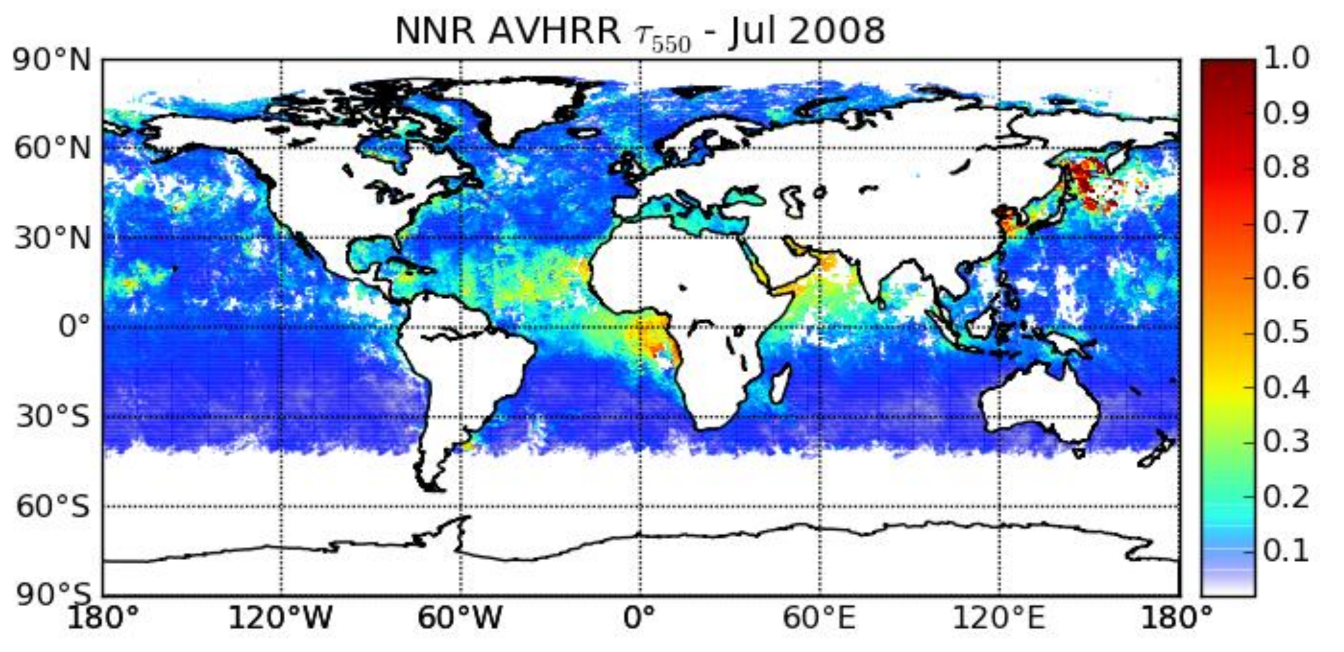


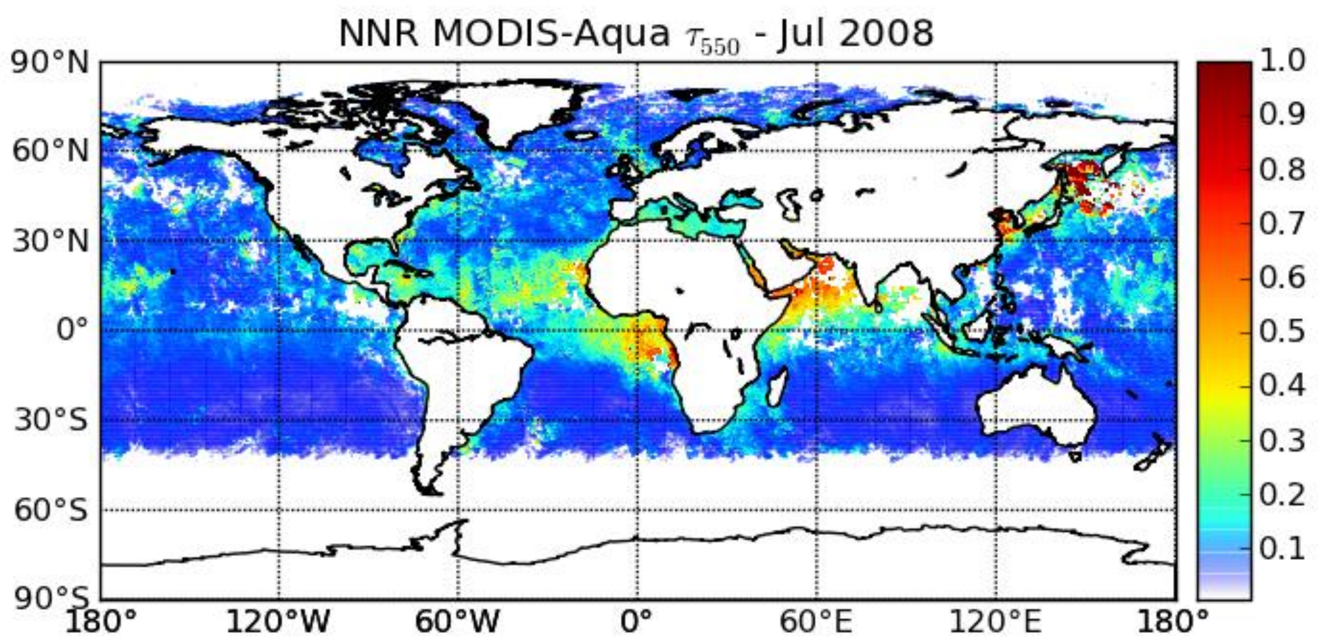




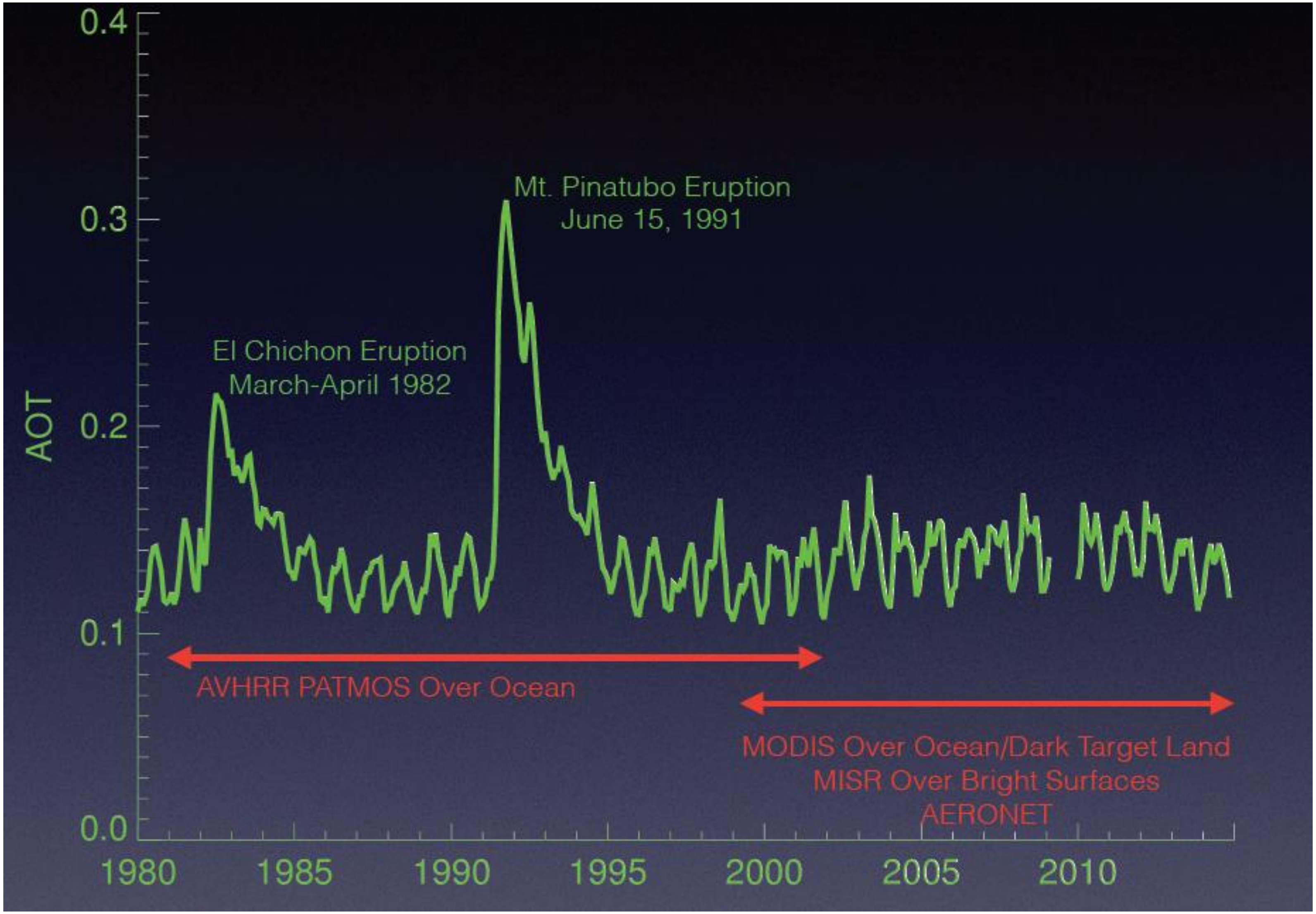
Multiple Species



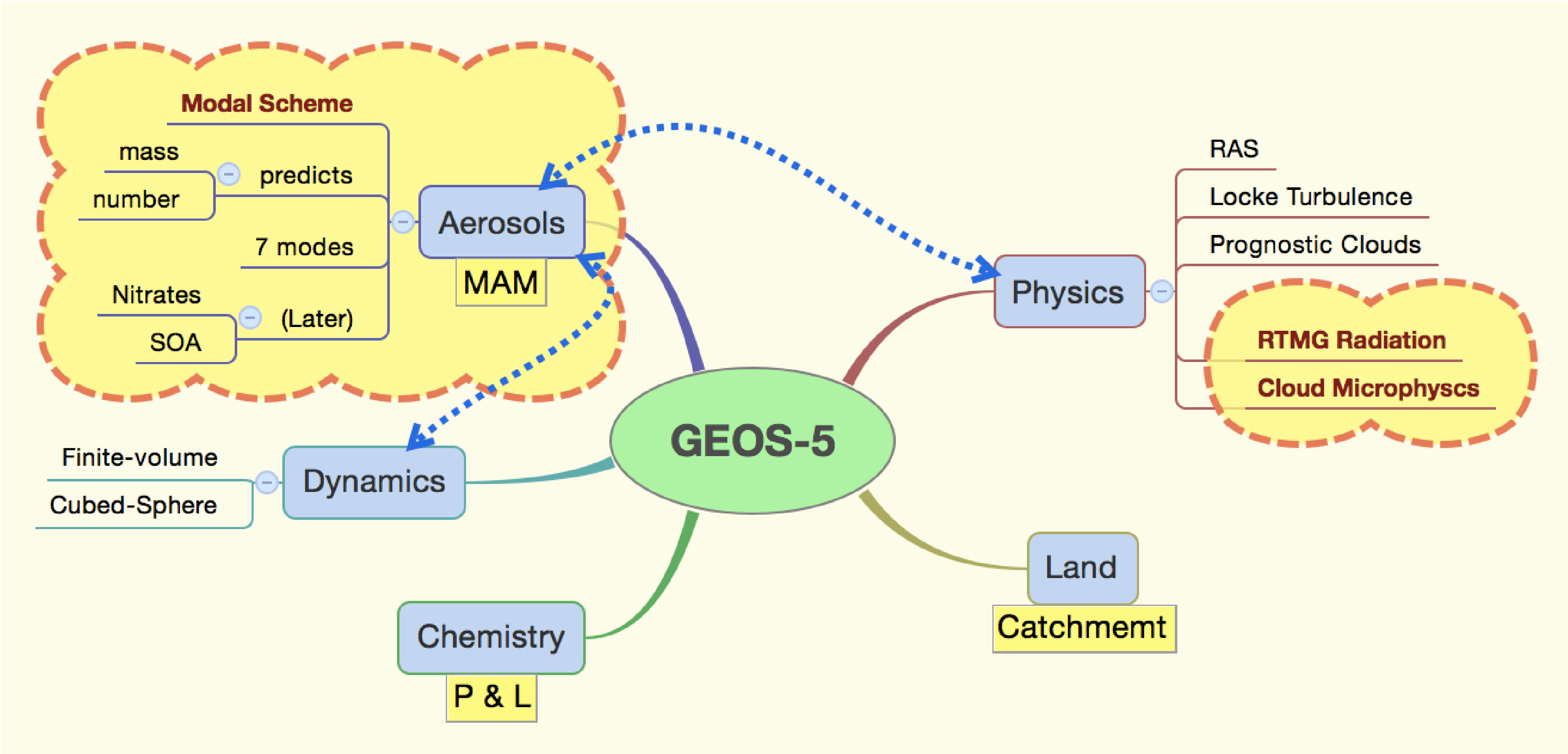

NNR AVHRR τ_{550} - Jul 2008
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°
120°W
60°W
0°
60°E
120°E
180°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1


NNR MODIS-Aqua τ_{550} - Jul 2008
90°N
60°N
30°N
0°
30°S
60°S
90°S
180°
120°W
60°W
0°
60°E
120°E
180°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1

MERRA-2 Global AOD



Current GEOS-5 Development: Aerosol & Clouds Microphysics



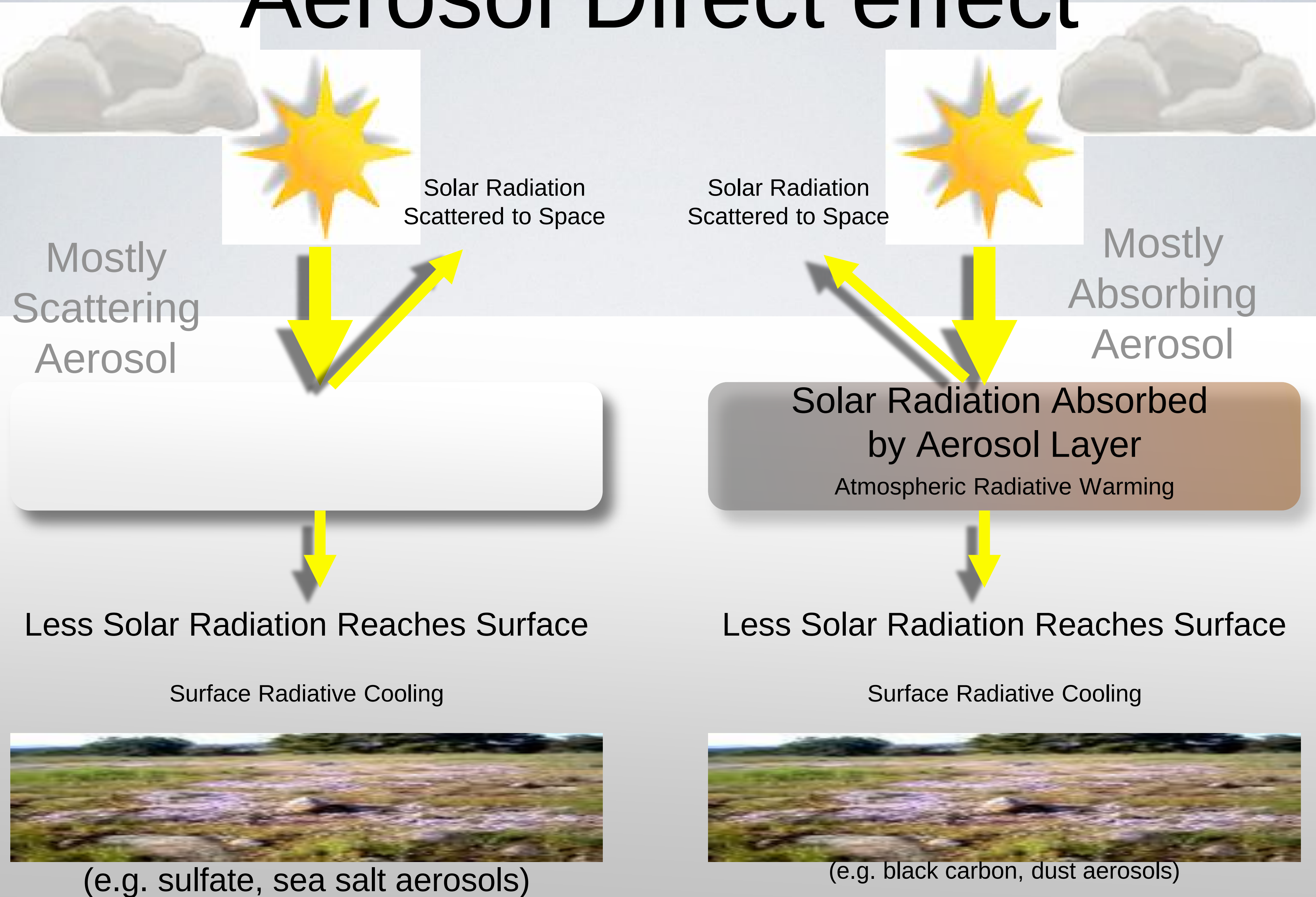
Global, **12.5 km**, **72** Levels, top at 0.01 hPa

Summary

- Aerosols are an integral part of the GEOS-5 N.R.T. and re-analysis systems
- MERRA-2 provides the first integrated aerosol-meteorology reanalysis for the satellite era
- Current GEOS-5 developments incorporate cloud and aerosol microphysics
  - Aerosol-cloud interactions, missing species
- Aerosol assimilation migrating to EnKF

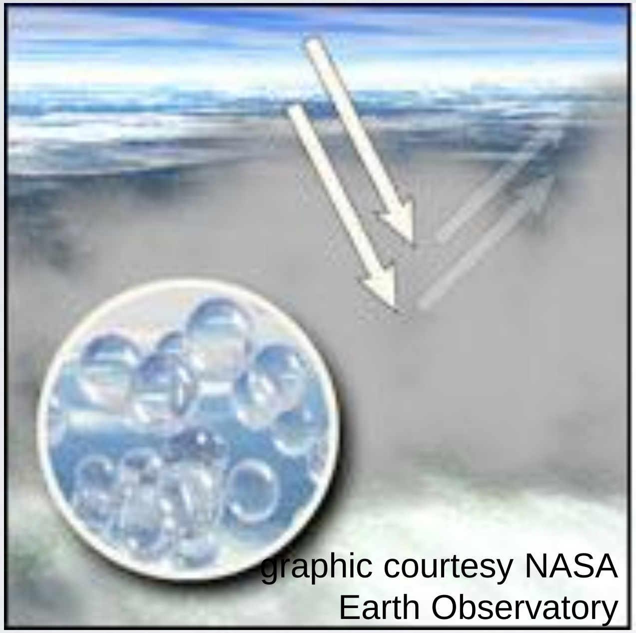
Extra Slides

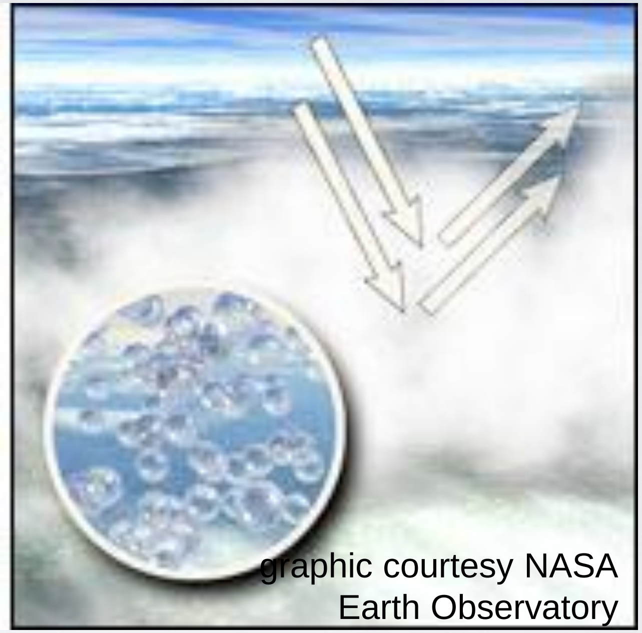
Aerosol Direct effect



Animation by C. A. Randles

Aerosol INDirect effect


graphic courtesy NASA
Earth Observatory


graphic courtesy NASA
Earth Observatory

Larger cloud
droplets,
less reflective cloud.

Twomey Effect

Smaller cloud
droplets,
more reflective cloud.

Less Aerosols

Increased Cooling by Clouds

More
Aerosols

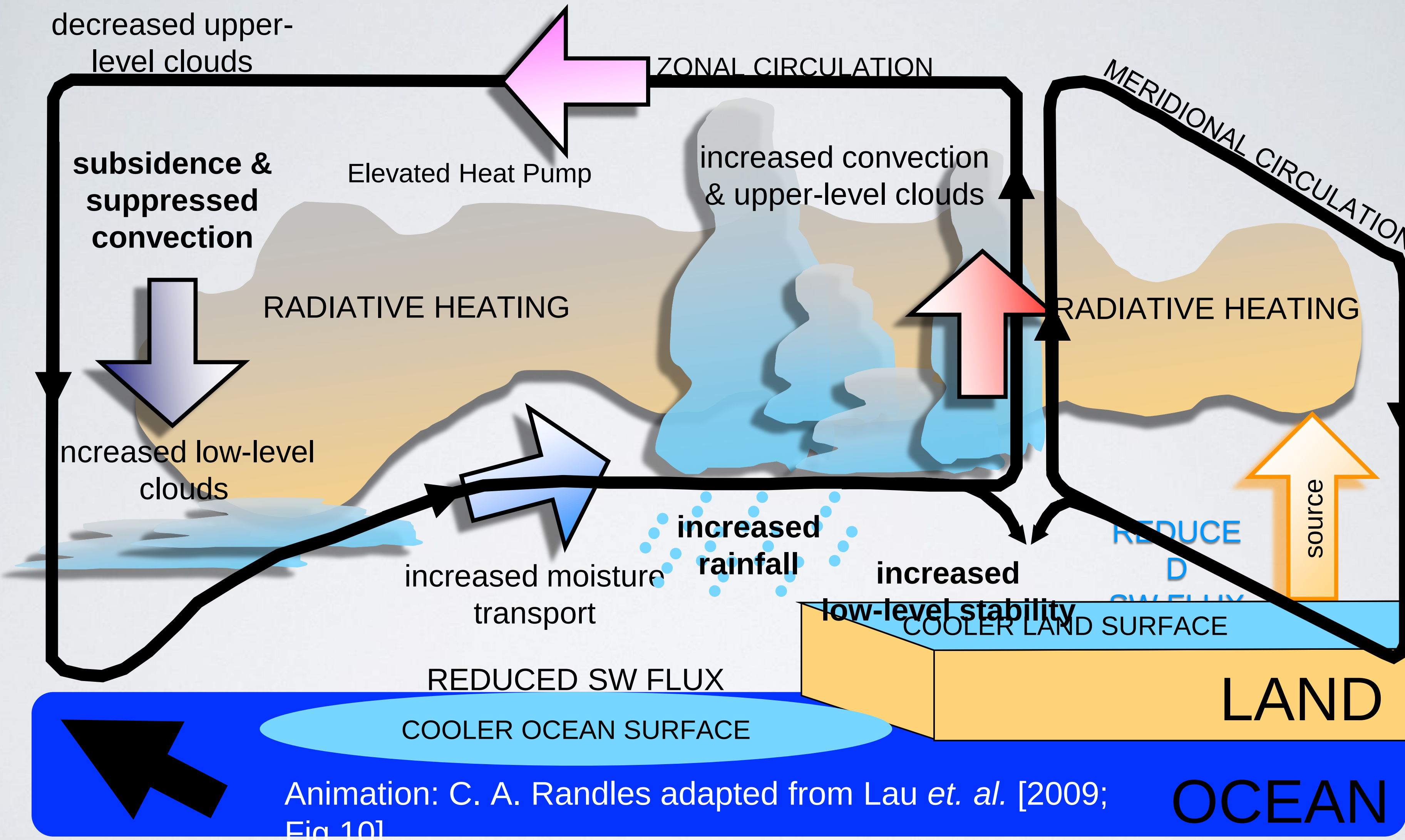
Larger cloud droplets,
droplets rain out
easier,
clouds dissipate
quicker.

Albrecht Effect

Smaller cloud
droplets,
droplets rain out less,
longer-lived clouds.

Animation by C. A. Randles

Absorption-CIRCULATION INTERACTIONS



Widespread absorbing aerosol layers can impact large-scale circulation and precipitation patterns like the Indian Monsoon (e.g. Ramanathan and Carmichael, *Nature*, 2008).

MERRAero
Aerosol Data Products

2D DATASETS

- Hourly, 3-hourly
- Speciated
  - AOT, AAOT, PM2.5, PM10
    - 12 wavelengths
    - 340, 380, 440, 470, 500, 550, 670, 865, 1024, 1240, 1640, 2130
  - Surface & column mass
  - Sources & sinks
- Non-speciated
  - Aerosol radiative forcing
  - UV aerosol Index

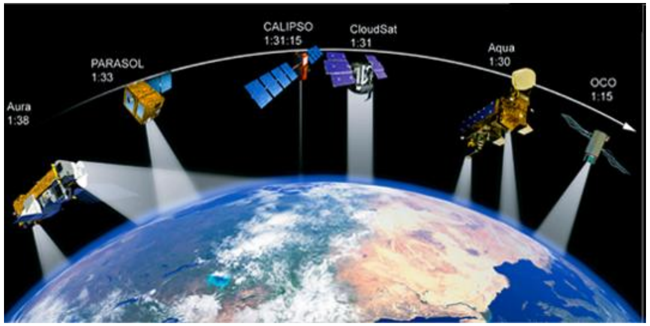
3D DATASETS

- 3-hourly
- Speciated:
  - Aerosol mixing ratio
- Non-speciated
  - 355nm, 532nm, 1024nm
  - Aerosol Extinction
  - Single Scattering Albedo
  - Asymmetry parameter
  - Backscatter
  - Attenuated Backscatter (TOA & SFC)

ftp://iesa@ftp.nccs.nasa.gov/pub/MERRAero

Aerosol Data Assimilation: MERR*Aero* Configuration

- Focus on NASA EOS instruments, MODIS for now



- Global, high resolution 2D AOD analysis
- 3D increments by means of Local Displacement Ensembles (**LDE**)

- Simultaneous estimates of background bias (*Dee and da Silva 1998*)
- Adaptive Statistical Quality Control (*Dee et al. 1999*):
  - State dependent (adapts to the error of the day)
  - Background and Buddy checks based on log-transformed AOD *innovation*
- Error covariance models (*Dee and da Silva 1999*):
  - Innovation based
  - Maximum likelihood

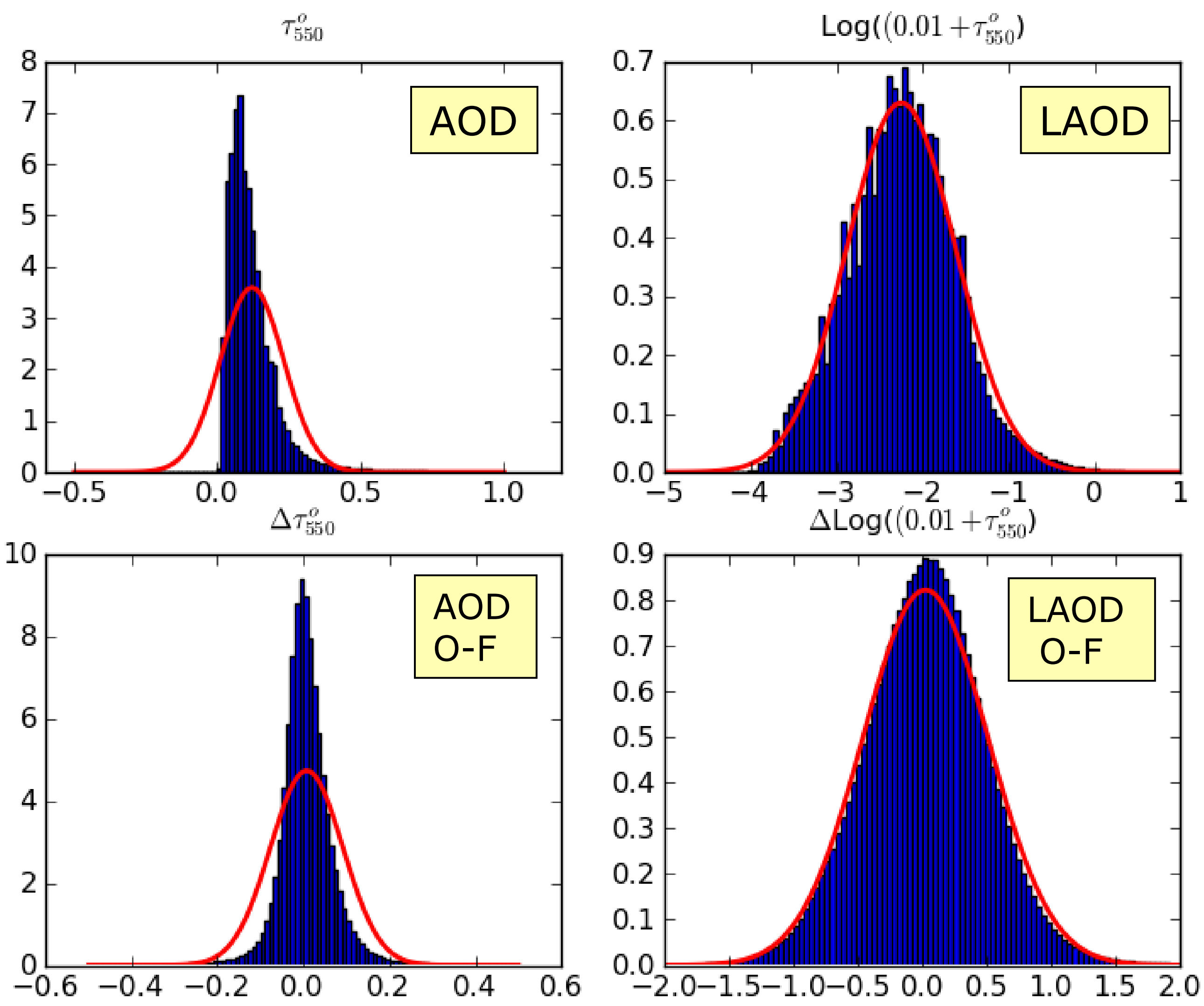
Data Type

- Quality control and Data Assimilation methodologies assumes Gaussian statistics
- AOD (and errors) is not normally distributed
- *Log-transformed* AOD has better statistical properties:

$$\boxed{\text{Log}\ (\ 0.01 + \text{AOD})}$$

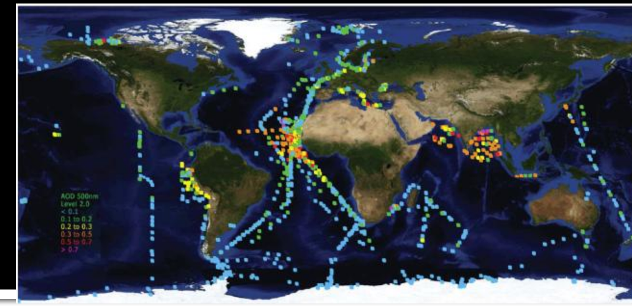
- This 0.01 factor is determined from *goodness-of-fit* considerations

Analysis Variable: $h = \log(t + 0.01)$

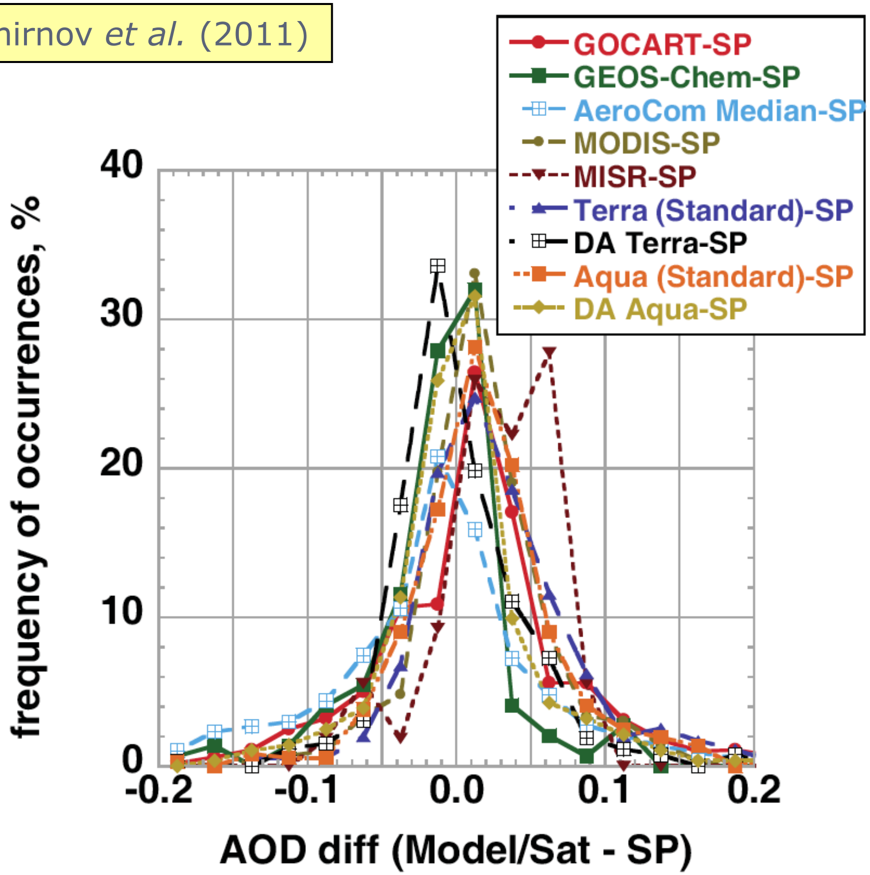


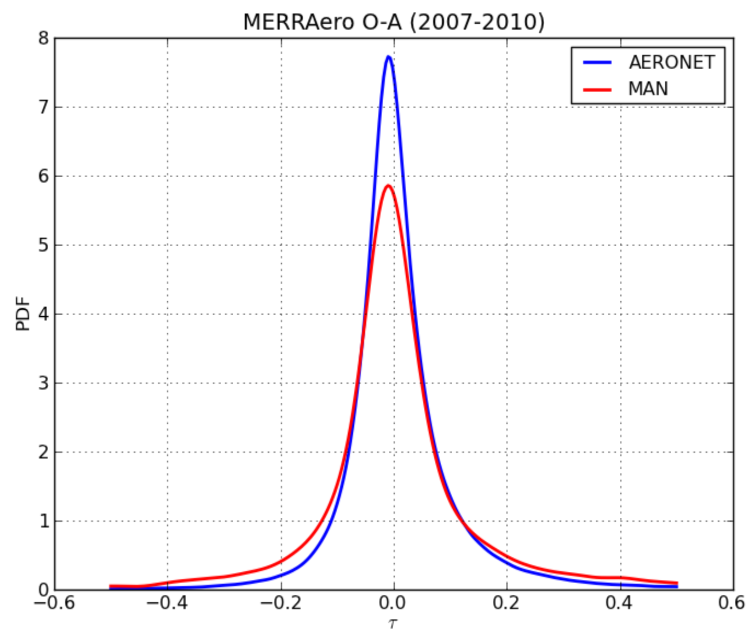
MODIS/TERRA Ocean

Maritime Aerosol Network

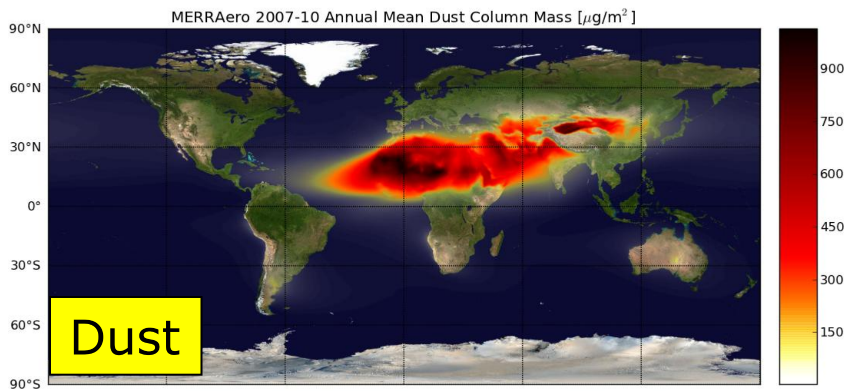


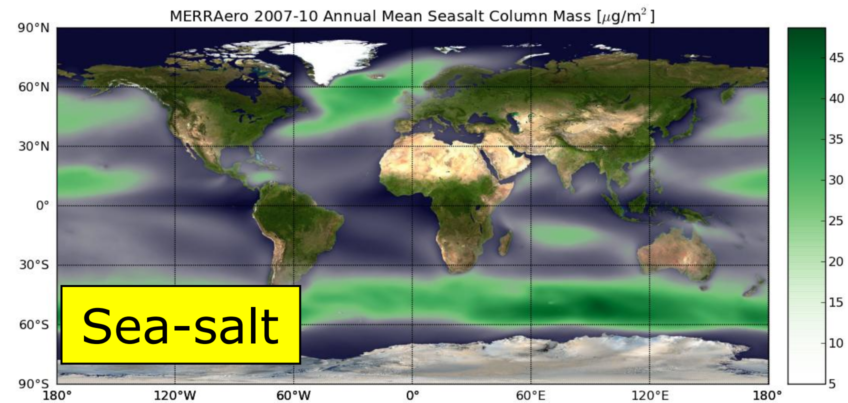
Smirnov *et al.* (2011)

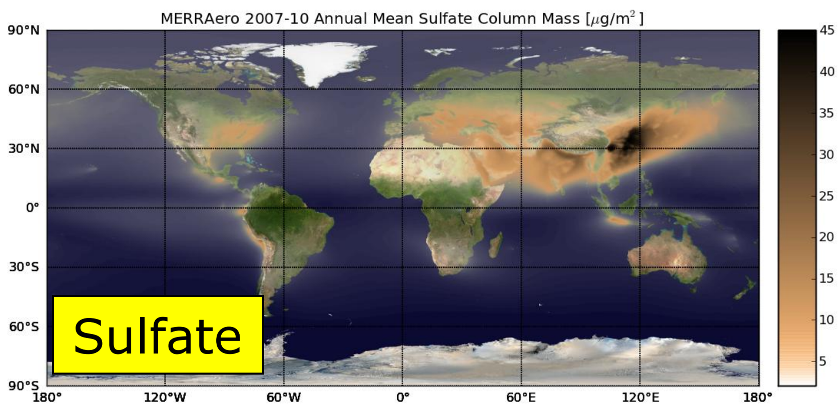


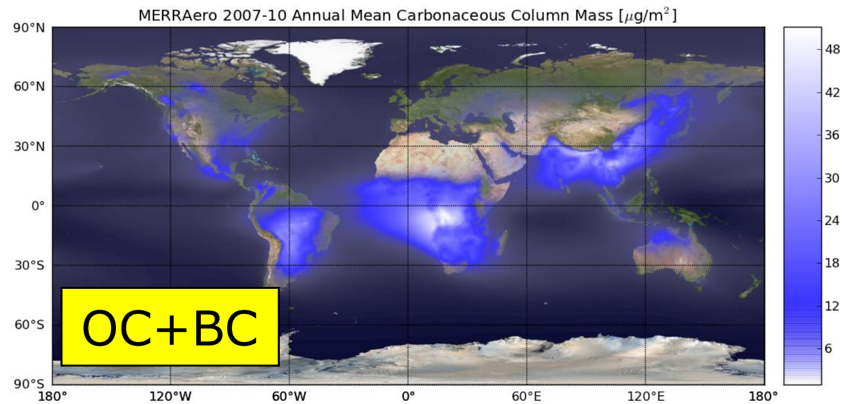


Assimilated Aerosol Annual Mean Mass









Speciation potentially adjusted by spectral reflectances

Mass Budget

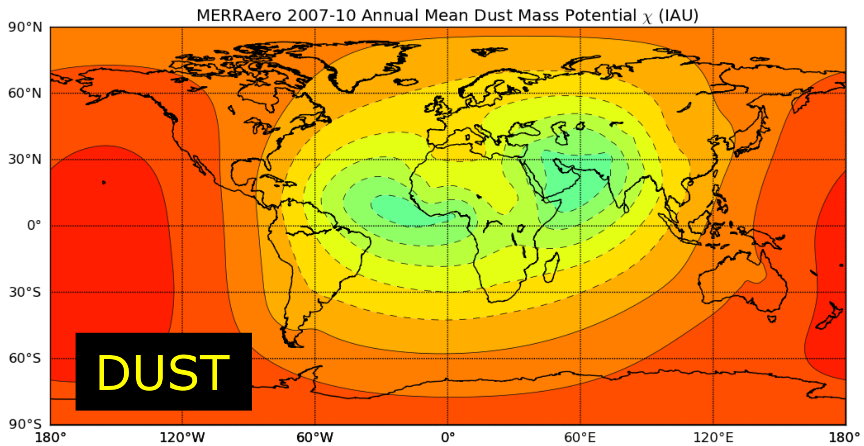
Annual mass budget for an aerosol specie q:

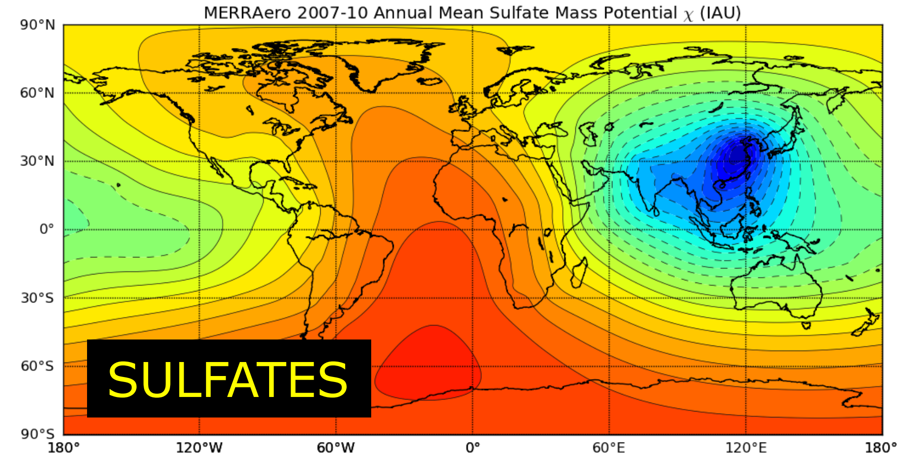
$$\nabla \cdot \overline{\langle \mathbf{u}q \rangle} = \overline{E} + \overline{P} - \overline{L} + \frac{\overline{\langle \Delta q^a \rangle}}{\tau}$$

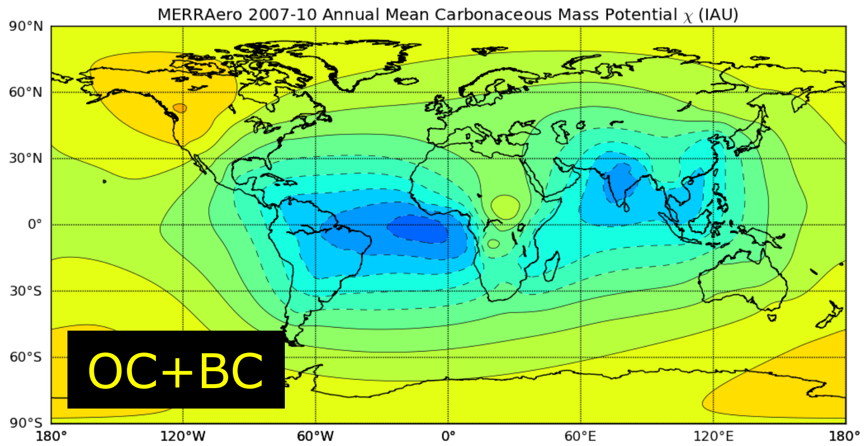
where

$\mathbf{u}q$	Mass flux
E	Emissions
P	Chemical production
L	Loss processes
Δq^a	Anaysis increments
τ	Analysis interval (3 hours)
$\langle \cdot \rangle$	Mass weighted vertical integral
$\overline{(\cdot)}$	Time average

Annual Mean Analysis Increments

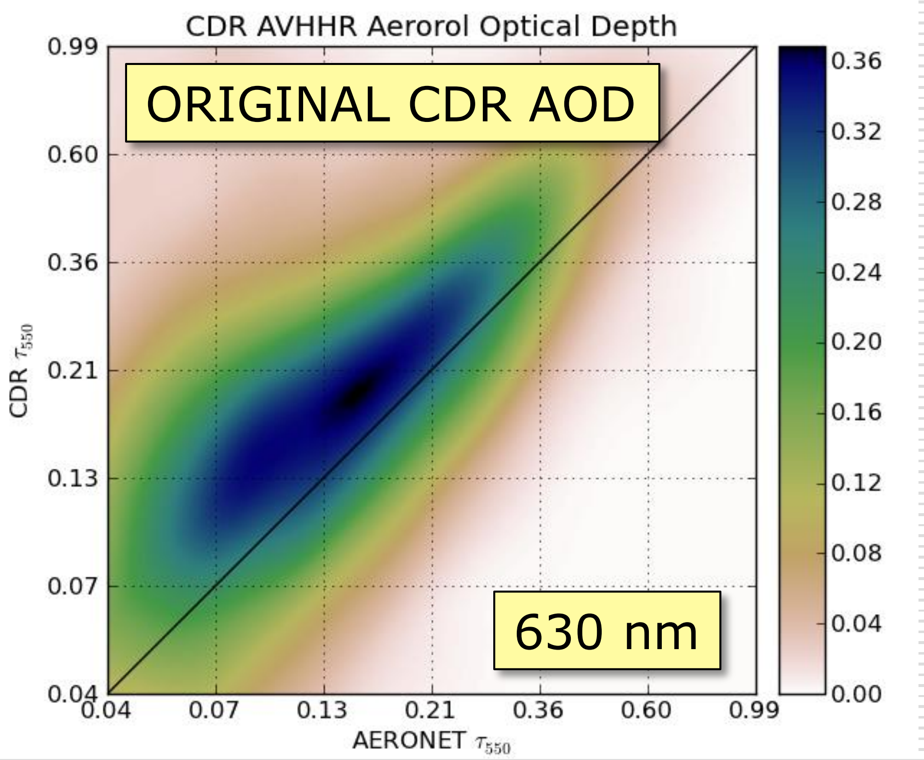


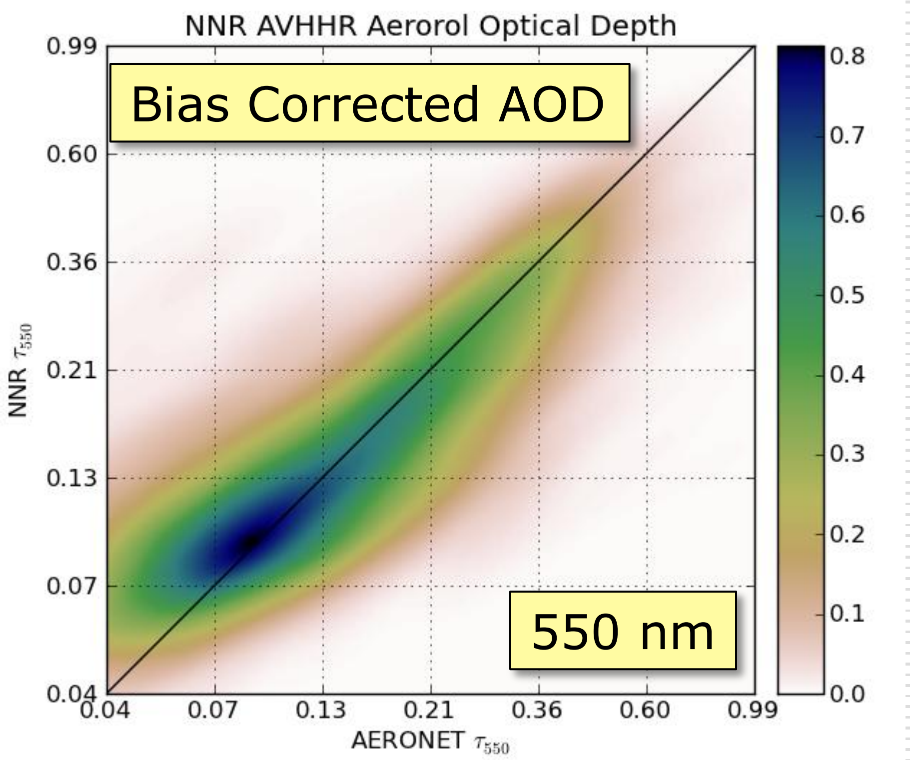




$$\chi = \nabla^{-2}\left[\left(\overline{E} + \overline{P} - \overline{L} + \frac{\langle \Delta q^a \rangle}{\tau}\right]\right.$$

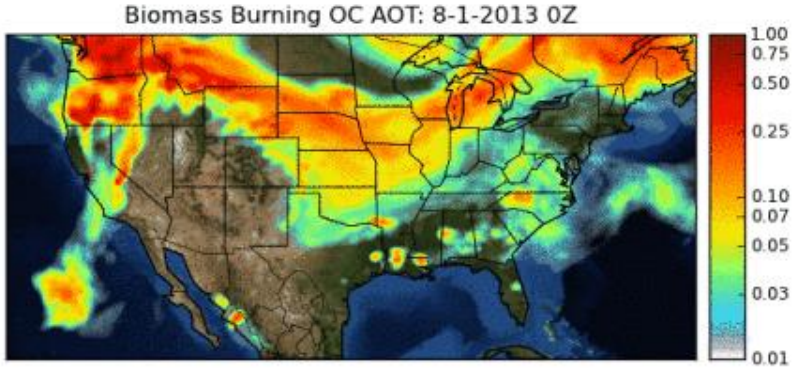
AVHRR NOAA CDR AOD
AERONET Comparison



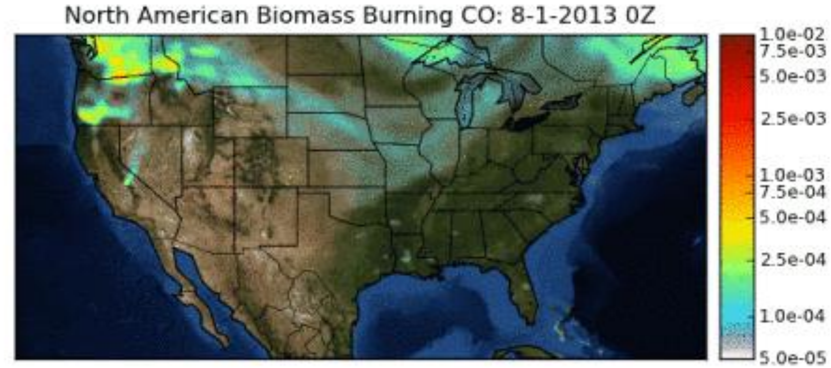


Coastal and Island Stations for 2003-2009

GEOS-5 SEAC^{4}RS Mini-Reanalysis



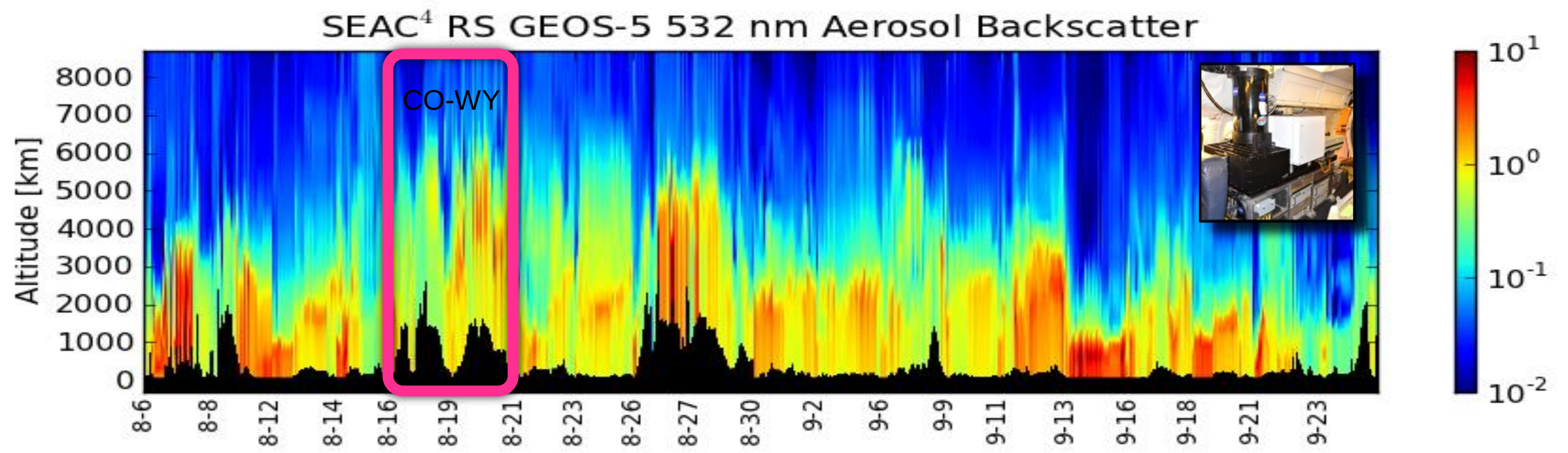
GEOS-5 Biomass Burning OC AOT

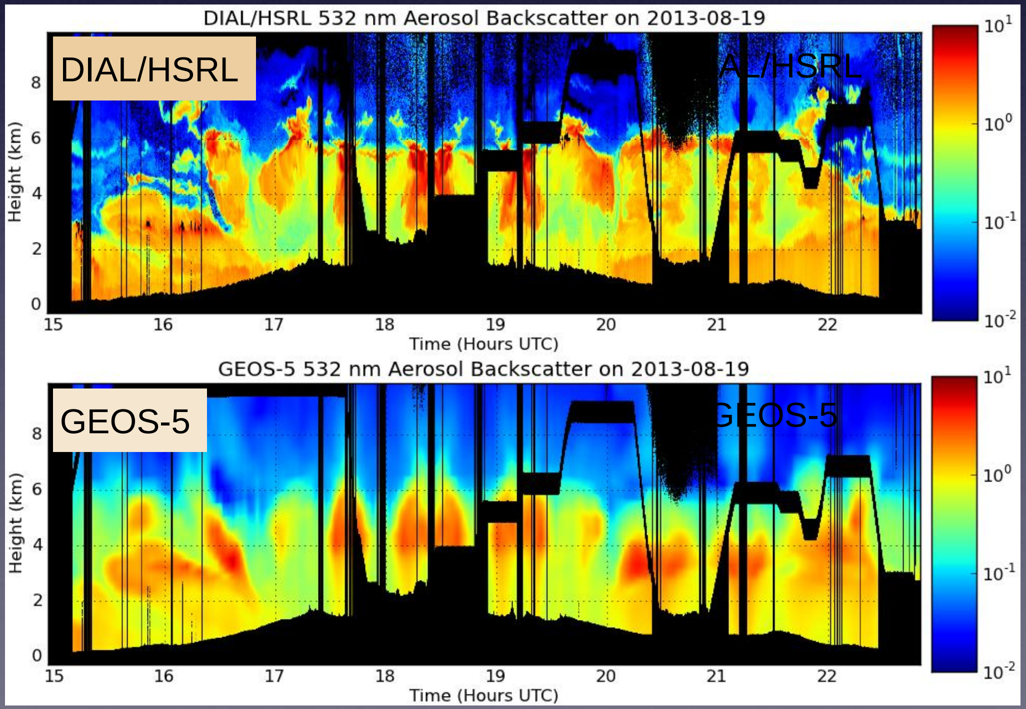


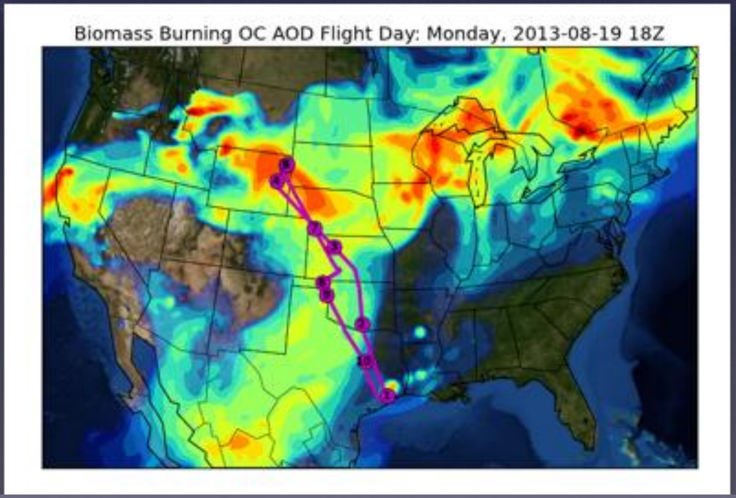
GEOS-5 Biomass Burning CO from N. America

Feature	Description
Model	**GEOS-5** Earth Modeling System with **GOCART** aerosols coupled to radiation parameterization
Fire Emissions	**QFED: Daily, NRT, MODIS FRP based**
Met. Data Assimilation	Full NWP observing system (uses GSI)
Aerosol Data Assimilation	**Assimilates 550 nm AOT, Local Displacement Ensembles (LDE), Adaptive Buddy Check**
Aerosol Observing System	**MODIS: Aqua & Terra Neural Net Retrievals (NNR)** **MISR: Bright surfaces only (albedo > 15%)** **AERONET: Level 2**
Resolution	~25 km (0.5° × 0.625° latitude × longitude), 72 layers, top ~85 km
Aerosol Species	Dust (DU), sea-salt (SS), sulfates (SO_4), organic and black carbon (OC and BC)
Carbon Species	CO_2, CO with several geographically tagged tracers
Smoke "Age" Tracers	**Provides "age" of un-assimilated biomass burning OC AOT with 1 day time resolution (smoke "age" histogram)**

Vertical Distributions: DIAL/HSRL 532 nm Backscatter

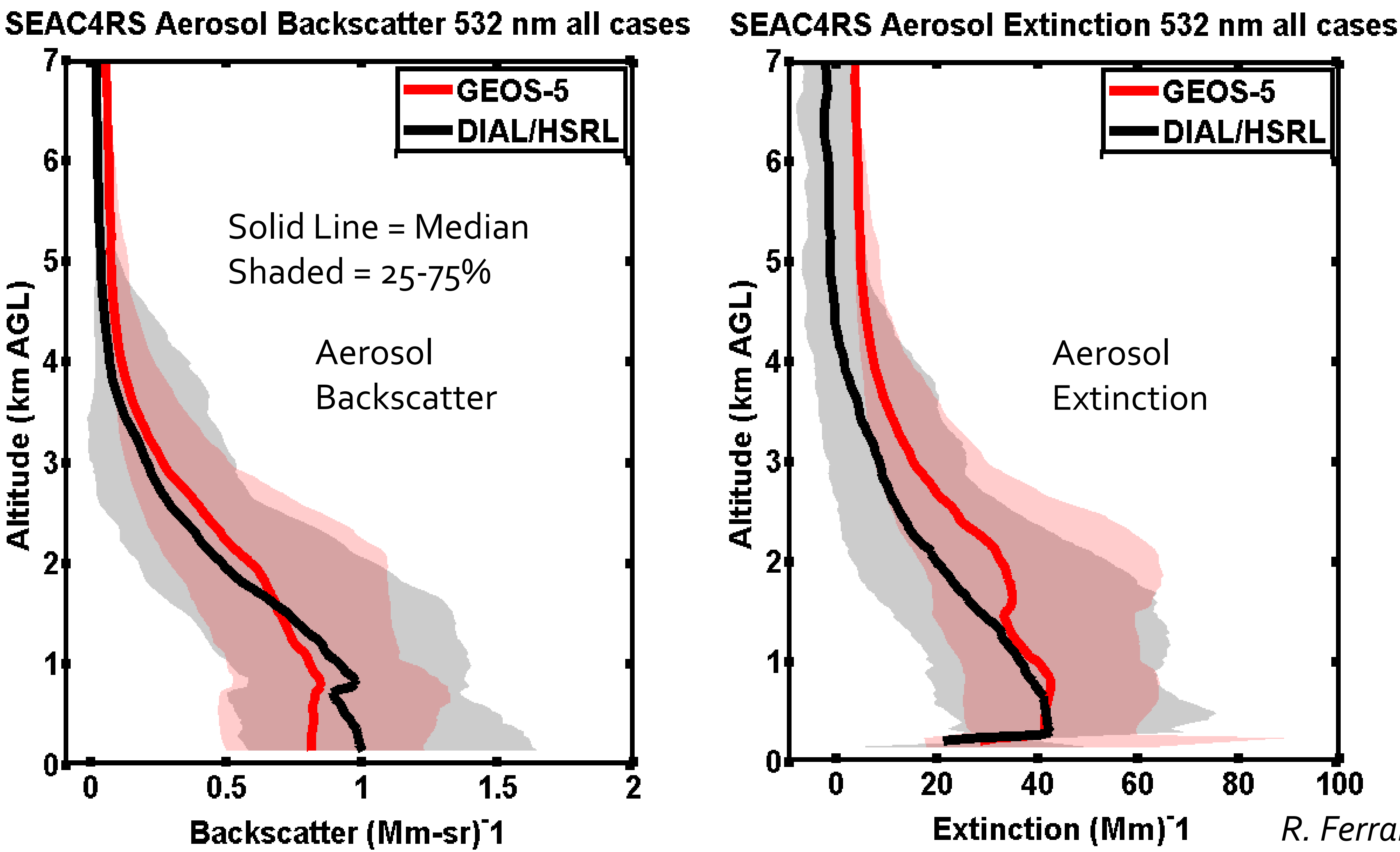






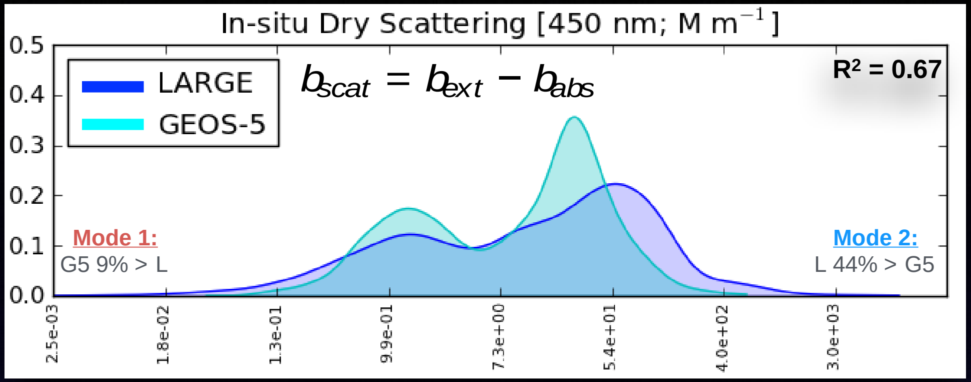
DIAL/HSRL and GEOS-5 Median Backscatter and Extinction Profiles During SEAC4RS

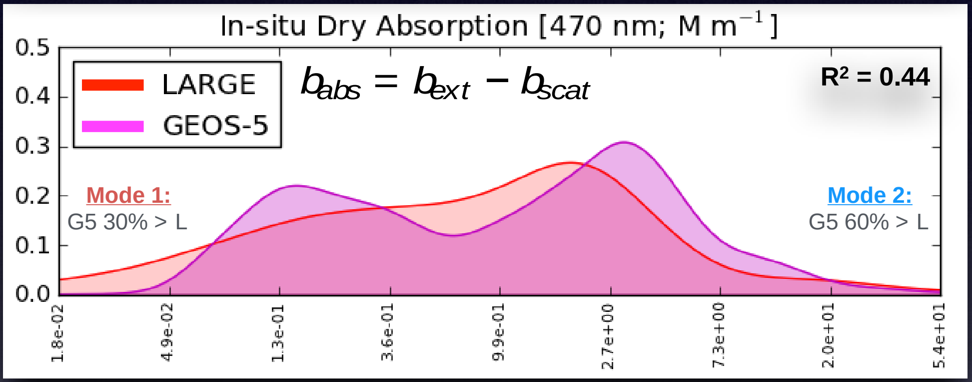
GEOS-5 shows slightly higher backscatter and extinction in free troposphere

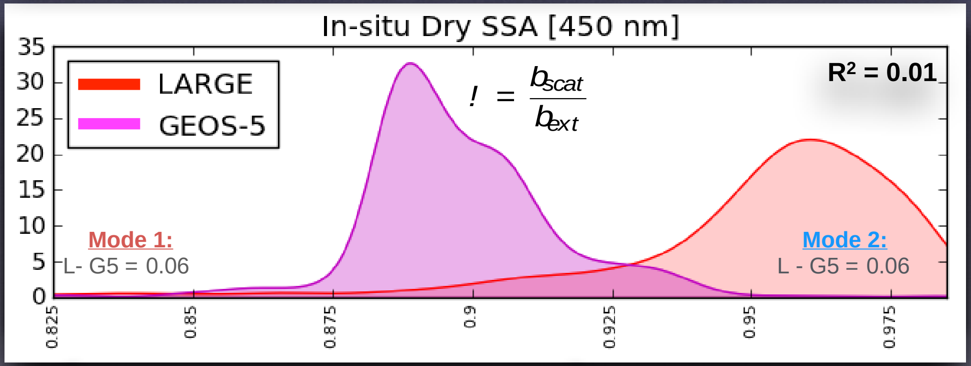


R. Ferrare

In-Situ Aerosol Optics: LARGE (450 - 470 nm) Dry PDFs







Characteristic	Mode 1	Mode 2
OC/BC Carbonaceous Mass	79% OC 21% BC	93% OC 7% BC
% Total Mass BC	0.04	0.02
BC Hygroscopicity	17% Hydrophobic 83% Hydrophilic	35% Hydrophobic 65% Hydrophilic
Smoke 0-2 d	0.09	0.29
Smole 6-7+ d	0.69	0.35

Mode 1 ⇒ Mode 2

Less Absorption ⇒ More Absorption

Lower SSA ⇒ Higher SSA

More BC ⇒ Less BC

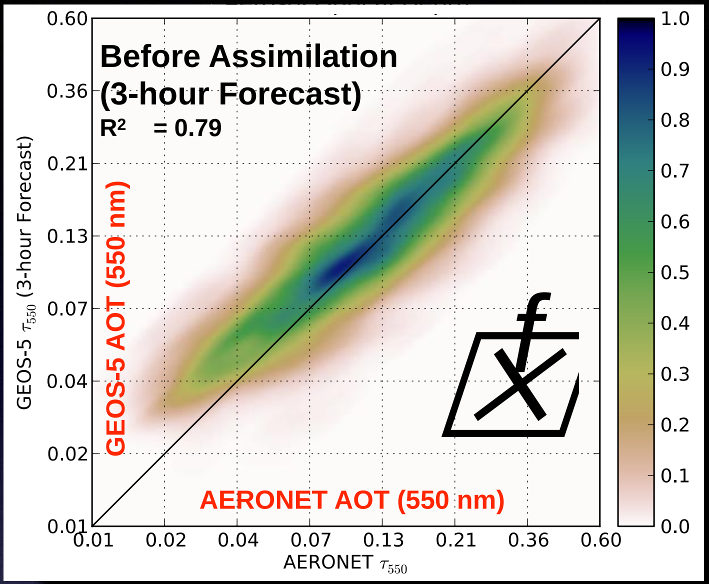
More Hydrophilic ⇒ More Hydrophobic

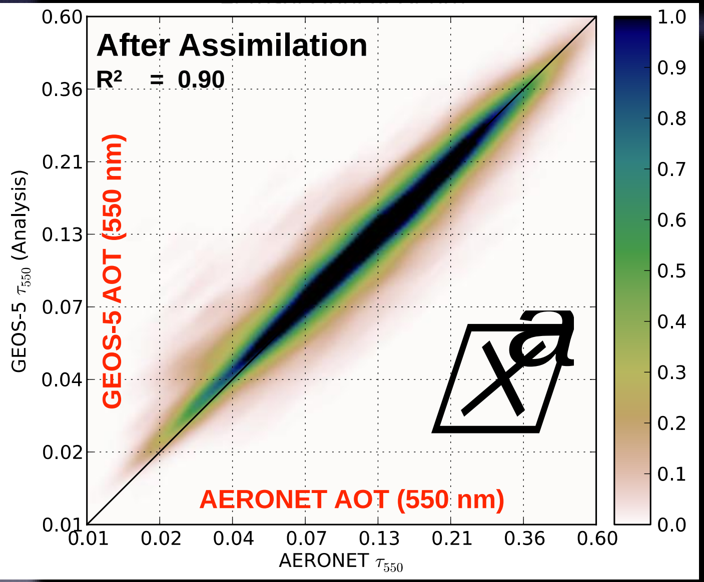
Old ⇒ Young

Aerosol Observing System Statistics

Observing System	GEOS-5 AOT	Statistics (130°W-60°W, 24°N-55°N) R^2	1000 × stderr	Bias (Obs-GEOS5)
AERONET N = 102,552	Background	**0.79**	1.25	-0.06
	Analysis	**0.9**	0.92	-0.02
MISR N = 494,743	Background	**0.66**	0.9	0.06
	Analysis	**0.83**	0.58	0.02
MODIS Terra N = 24,504,880	Background	**0.72**	0.1	-0.12
	Analysis	**0.92**	0.05	-0.01
MODIS Aqua N = 23,300,505	Background	**0.74**	0.1	-0.08
	Analysis	**0.93**	0.05	0

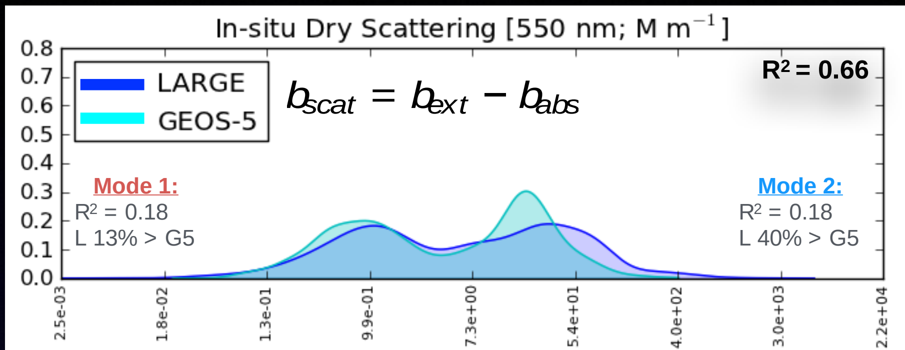
- Effect of observing system on the 3-hr forecast skill (**N.B.:** 3-hr forecast informed by previous assimilation step)
- After assimilation, comparison is not 1-to-1 because of impact of other sensors.



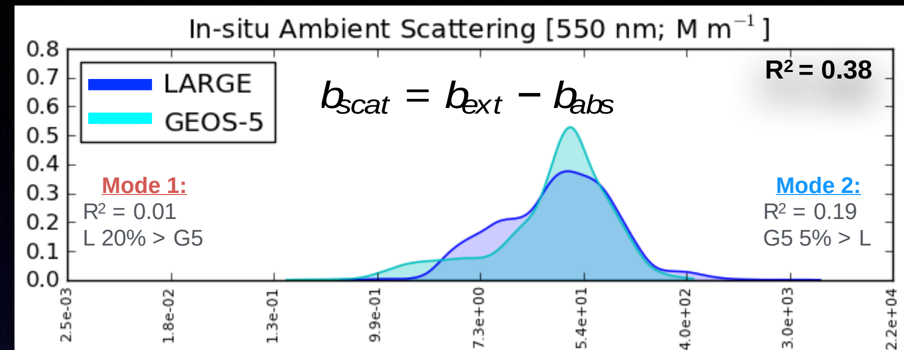


In-Situ Aerosol Optics: LARGE (550 nm) and *f(RH)* PDFs

DRY AEROSOL



WET AEROSOL



Mode 2:
R^2 = 0.01
L - G5 = 0.06

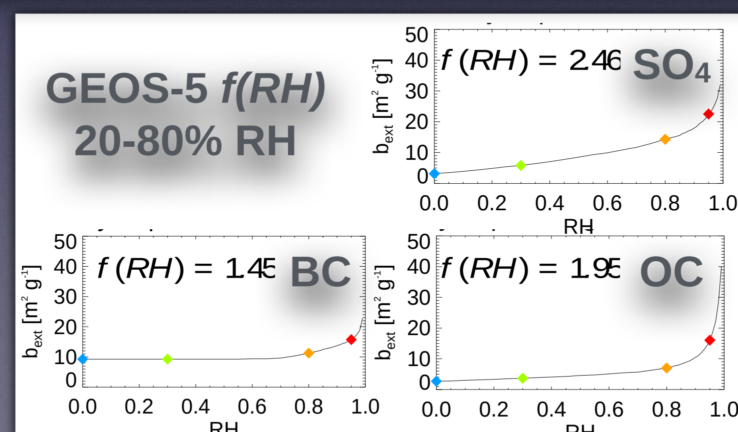
Mode 1:
R^2 = 0.11
L - G5 = 0.08

Mode 1:
R^2 = 0.01
L - G5 = 0.01

Mode 2:
R^2 = 0.00
L - G5 = 0.02

Mode 2:
R^2 = 0.15
G5 62% > L

Mode 1:
R^2 = 0.03
G5 63% > L



Fresh Smoke